# A GIS approach to landslide hazard management for the West Coast region, New Zealand.

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# Abstract

Landslides, in their various forms, are a common hazard in mountainous terrain, especially in seismically active areas and regions of high rainfall. The West Coast region of New Zealand is dissected by many active faults, experiences frequent earthquakes and in many locations annual rainfall exceeds ten meters. Consequently, landslides are widespread in the region and since European settlement began, have been responsible for 27 deaths, along with frequent damages to road and rail infrastructure, settlements and agricultural land.

This study identifies areas that are susceptible to rainfall triggered landslides in the West Coast region. To achieve this, a landslide susceptibility map was produced using bivariate statistics and the analytical hierarchy process. It has an accuracy that predicts 80% of all the landslides in the top 40% of the susceptibility scores on the map. As part of this process, 3221 rainfall triggered landslides and 522 earthquake (or other trigger) triggered landslides have been mapped and digitised into a Geographic Information System. In parallel with this, a descriptive historical catalogue of 1987 landslides has been compiled from the available sources.

These new tools provide decision-makers with an enhanced means of managing landslide hazards in the West Coast region. In order to avoid misinterpretation the study has been carried out in compliance with the "Guidelines for landslide susceptibility, hazard and risk zoning for land use planning", which was published in 2008 by the Joint Technical Committee on Landslides and Engineered Slopes. The tools developed in this thesis represent a fundamental step in land-use planning and set-up of landslide hazard management in the West Coast region.

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# Chapter 1. Introduction

## 1.1 Context and background

Landslides, in their various forms, are a common hazard in mountainous terrain, especially in seismically active areas and regions of high rainfall. The West Coast region of New Zealand is dissected by many active faults, experiences frequent earthquakes and in many locations annual rainfall exceeds 10m. Consequently, landslides are widespread in the region and since European settlement began in the $19^{th}$ century have been responsible for 27 deaths, along with frequent damages to road and rail infrastructure, settlements and agricultural land (Benn, 2005). The continuing residential and commercial development of hilly country throughout the region combined with the increasing value of real estate has highlighted the need for better understanding of landslide occurrence and distribution. Figure 1.1 shows the devastation caused by the fatal Whitecliffs landslide in 1968.

In order to fulfil its responsibilities under the Resource Management Act 2002 (RMA), the West Coast Regional Council (WCRC) commissioned DTEC Consultants to write the West Coast Regional Council Natural Hazards Review, which described the various natural hazards that affect the region and provided a base for future research (DTEC, 2002). It collated all the available information pertaining to natural hazards and highlighted information gaps. Various points were made relating to landslides in the region and defining the relationships between rainfall, slope aspect and angle, soil and rock types, to the distribution and size of landslides was noted as a priority (DTEC, 2002). The production of landslide hazard maps was also identified as an important step towards managing the landslide hazard in the region.

Perhaps due to the frequency of landslides, unique landscape and meteorological conditions the West Coast Region has attracted much attention from geomorphologists, geographers and geologists (eg. Chevalier *et al*., 2009; Korup, 2004, 2005; Hovius *et al.,* 1997; Santamaria *et al.*, 2008) who have provided a great amount of useful information on the landslide characteristics of the region. It has been shown that rainfall is by far the most common trigger mechanism, but earthquake generated landslides have been given the most attention by researchers. There have also been numerous site-specific geotechnical investigations (eg. Power and Anderson, 1992; Cooper, 2000; Yetton, 1999; Smith, 2004), which have provided hazard guidance for landslide prone developments and infrastructure in their study areas. John Benn (2005) produced a landslide catalogue detailing the historical occurrences of landslides in the region and used this to make the first regional characterisation of landslide risk making observations relating to frequency of damages caused by landsliding, common trigger mechanisms and areas most at risk.

This study elaborates on Benn's work by further developing the historical landslide catalogue, and has delineated landslide susceptibility by mapping the spatial distribution of landslides from aerial photography, other research, direct observations, etc. and comparing this landslide inventory to mapped terrain variables within a Geographic Information System (GIS). The relationships between the

**Figure 1.1** The fatal Whitecliffs landslide in the Buller District, 1968. Photograph courtesy of Nelson Provincial Museum.

landslide distribution and the terrain variables that contribute to landscape instabilities are explored using bivariate statistics, and a landslide susceptibility map has been produced illustrating the relative susceptibility of the landscape to landslides triggered by rainfall. This is the first landslide susceptibility map for the region and will be used as an aid to decision-making in development planning by the three Territorial Local Authorities (TLA's), the West Coast Regional Council (WCRC), and by civil defence staff for emergency planning.

This research has been carried out in conjunction with the WCRC, funded in part by Envirolink. The techniques described could be used to delineate the landslide potential in other regions where landsliding is a problem.

## 1.2 Objectives

The aim of this thesis is to better understand and identify areas potentially prone to slope failure where there is development, or the potential for development, within the West Coast region. By developing and providing the necessary tools this thesis aims to improve the landslide hazard management capabilities of the decision-makers of the region. As yet, only landslide catalogues have been completed to be used as guidelines for hazard management, which has left the public, and development planners, in a position where decision-making on landslide vulnerability issues is not a well informed process. The thesis aims to establish a relationship between landsliding and the various landslide conditioning factors in the West Coast region. The result of this is to spatially define the specific hazard posed by landsliding in relation to known, mapped features such as topography, geology, soils, vegetation, land use, rainfall, etc. In addition to this, a landslide catalogue has been collated, which details all the known historic landslides in the region and presents them in a way that is easy to use for hazard management purposes.

In response to the information gaps highlighted in the WCRC Natural Hazards Review (DTEC, 2002), a regional landslide susceptibility map has been produced. This is the first rational landslide susceptibility map for this region. It also builds on the previous understanding of landslide distributions and frequency, by filling chronological and geographic gaps in the landslide catalogue records.

Another key objective of this study is to deliver the findings of this new tool to the decision-makers of the region, via a series of workshops, to ensure that it can be used effectively for landslide hazard management. This has been achieved by producing a usage manual and delivering presentations explaining the research, modelling and mapping methods, limitations and usefulness of the landslide susceptibility map and landslide catalogue.

This thesis also illustrates the methods by which these new tools can be used by local Government for effective landslide hazard management. It shows, via a case study of the coastal strip between Waimangaroa and Nikau, how the susceptibility map can be used in conjunction with the newly-compiled landslide catalogue to better define the risk to people and infrastructure in highly susceptible areas.

In order to maximize the usefulness and accuracy of this thesis, the study was conducted in compliance with the “Guidelines for landslide susceptibility, hazard and risk zoning for land use planning”, which was published in 2008 by the Joint Technical Committee on Landslides and Engineered Slopes (JTC-1). That document gives guidance on the methods, terminology and definitions that are now internationally accepted as a standard for landslide susceptibility, hazard and risk zoning studies. It also gives descriptions of the types and levels of landslide zoning, suggested mapping scales, types of information required and defines the reliability, validity and limitations of the methods that can be used to perform landslide susceptibility, hazard and risk zonation analysis (Fell *et al.,* 2008).

A secondary objective of this study is to appraise and test the validity of the technique used to produce the landslide susceptibility maps. This has been accomplished by testing the predictive power of the maps using a technique called the success rate curve (Chung and Fabbri, 2008), and performing a validation by mapping landsides from a new set of aerial photographs that were not used in the original landslide inventory compilation and critically observing the success rate of prediction.

## 1.3 Terminology

The term, landslide, is used to describe any uncontrolled movement of rock, debris or soil down a slope. However, the need for a clear understanding of the terminology of landslides has been noted by many authors (eg. Crozier, 1988; Varnes, 1978) and as a response to this, classifications of landslide types have been proposed to facilitate unambiguous communication and reporting of landslide occurrences. Table 1.1 shows an abbreviated version of the classification system designed by Cruden and Varnes (1996), which has become accepted as the standard means of describing the form of landslides.

**Table 1.1** Types of landslides. Abbreviated version of Cruden and Varnes' classification of landslide types (Cruden and Varnes, 1996).

<table>
<tr><th colspan="2" rowspan="3">Type of movement</th><th colspan="3">Type of material</th></tr>
<tr><th rowspan="2">Bedrock</th><th colspan="2">Engineering soils</th></tr>
<tr><th>Predominantly coarse</th><th>Predominantly fine</th></tr>
<tr><td colspan="2">Falls</td><td>Rock fall</td><td>Debris fall</td><td>Earth fall</td></tr>
<tr><td colspan="2">Topples</td><td>Rock topple</td><td>Debris topple</td><td>Earth topple</td></tr>
<tr><td rowspan="2">Slides</td><td>Rotational</td><td rowspan="2">Rock slide</td><td rowspan="2">Debris slide</td><td rowspan="2">Earth slide</td></tr>
<tr><td>Translational</td></tr>
<tr><td colspan="2">Lateral spreads</td><td>Rock spread</td><td>Debris spread</td><td>Earth spread</td></tr>
<tr><td colspan="2">Flows</td><td>Rock flow</td><td>Debris flow</td><td>Earth flow</td></tr>
<tr><td colspan="5">Complex: a combination of two or more principal types of movement</td></tr>
</table>

The JTC-1 guidelines on the terminology of landslide hazard and the various methods to assess the effects of landslides have been followed and to avoid the confusion that can arise from the common misuse of terms such as “hazard” and “risk”.

The use of GIS for the analysis of landslide susceptibility also requires quite specific terminology.

Definitions of the main terms are:

***Buffer:*** A zone around a map feature measured in units of distance or time. A buffer is useful for proximity analysis.

***Hazard***: The probability or likelihood of a potentially damaging event occurring in a unit of time. Hazard is often expressed as the probability of occurrence of a given magnitude of event.

***Landslide catalogue:*** An historical list of landslides with dates and information relating to type of movement, size, damage caused, trigger, remedial measures in place, and any other pertinent information. It is usually compiled from newspaper records, maintenance records, etc.

***Landslide inventory*****:** A spatial dataset of mapped landsides (often compiled from one trigger event), usually derived from aerial photograph interpretation (API), satellite image interpretation, and direct field mapping. It can also contain the same information types as a landslide catalogue.

***Landslide susceptibility:*** A quantitative or qualitative assessment of the classification, volume (or area), and spatial distribution of landslides which exist or potentially may occur in a given area. Although it is anticipated that landsliding will be more frequent in the more susceptible areas, timeframe is explicitly not taken into account in a susceptibility analysis.

***Overlay:*** A spatial operation within a GIS in which two or more maps or layers registered to a common coordinate system are superimposed for the purpose of showing the relationships between features that occupy the same geographic space.

***Raster:*** A spatial data model that defines space as an array of equally sized cells arranged in rows and columns, and composed of single or multiple bands. Each cell contains an attribute value and location coordinates. Unlike a vector structure, which stores coordinates explicitly, raster coordinates are contained in the ordering of the matrix. Groups of cells that share the same value represent the same type of geographic feature.

***Risk*****:** A measure of the probability and severity of an adverse effect to health, property or the environment. Risk is often estimated by calculating the probability of an event of a given magnitude multiplied by the consequences.

***Vector:*** A coordinate-based data model that represents geographic features as points, lines, and polygons. Each point feature is represented as a single coordinate pair, while line and polygon features are represented as ordered lists of vertices.

Attributes are associated with each vector feature, as opposed to a raster data model, which associates attributes with grid cells.

***Vulnerability:*** The degree of loss to a given entity within the area affected by a landslide. For property it will be expressed as the damage relative to the value of the property; for people it is expressed as the probability of loss of life.

***Zoning:*** The division of land into homogeneous areas and their ranking according to degrees of actual or potential landslide susceptibility.

## 1.4 Methodology

### 1.4.1 Landslide susceptibility mapping

A landslide susceptibility map depicts areas likely to have landslides in the future by correlating some of the principal factors that contribute to landslides with the past distribution of landslides (Yalcin, 2008). It relies on the trusted geological principle that "the past and the present are the keys to the future". That is, future landslides are most likely to occur under the same conditions that led to past and present landslides (Dai and Lee, 2002). The most commonly used methods in landslide susceptibility assessments are geomorphological hazard mapping, analysis of landslide inventories, heuristic or index-based methods, geotechnical or physically-based models and statistical models (Huabin *et al.,* 2005). Statistical modelling removes the subjectivity of expert opinion based assessments, but the reliability of the resultant maps depends on the amount and quality of available data, the working scale and the selection of the appropriate methodology of analysis and modelling (Yalcin, 2008).

Figure 1.2 shows the steps necessary to produce a landslide susceptibility map. Thematic factor maps representing the factors deemed to be important in the control of landslide occurrence are prepared in a GIS and after grouping the classes into sensible sets the maps can be rasterized in preparation for overlay analysis. Each factor map is overlayed with the landslide inventory and the density of landslides in each class is then calculated. Following this, a weight is applied to each class within each factor map and the resultant maps can then be overlayed to give a total

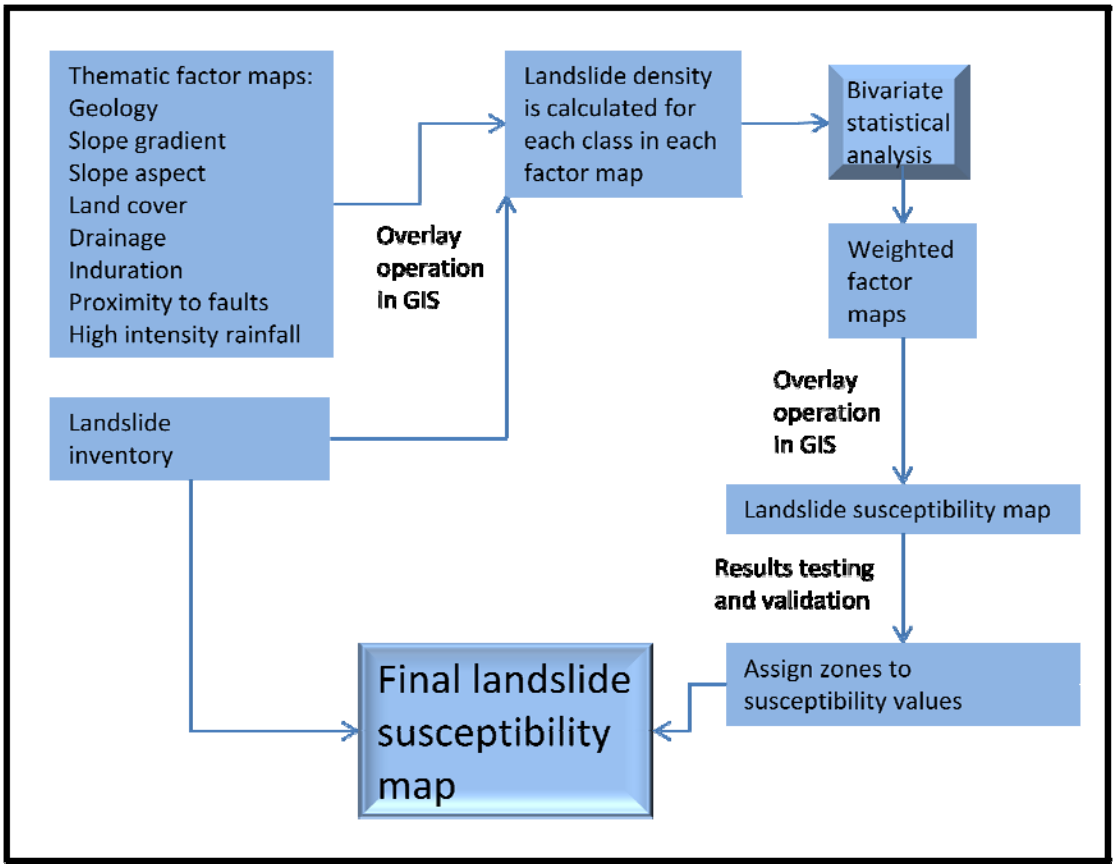



**Figure 1.2.** Simplified flow chart of the steps necessary to produce a landslide susceptibility map

susceptibility. This map can then be divided into zones representing low to high susceptibility to landsliding, based on a validation performed using a landslide distribution derived from new aerial photography.

### 1.4.2 Weights of evidence modelling and the analytical hierarchy process

This study utilises the "weights of evidence" method, which was first developed by Bonham-Carter (1994), for use in mineral potential assessment for the mining industry. It has also been used successfully to locate flowing oil wells, spatially define the relationship between faults and seismicity, and mapping cliff instabilities associated with mine subsidence (Dahal *et al.*, 2008). Since Van Westen *et al.* (2003) applied it to landslide susceptibility analysis, it has been successfully used for this purpose in many different and diverse study areas (Dai and Lee, 2002; Gullà *et al., 2008;* Neuhäuser and Terhorst, 2007; Nandi and Shakoor, 2009; Thiery *et al.,* 2007; Cevic and Topal, 2003, Suzen and Doyuran, 2004) producing landslide susceptibility maps that have been used for planning natural gas pipeline routes, land use planning and civil defence emergency planning.

Weights of evidence modelling is a bivariate statistical technique that uses the Bayesian probability model and calculates a weight for each landslide causative factor based on the presence or absence of landslides in the area. In bivariate statistical analysis, each factor's influence on landsliding is considered separately and the assumption is made that the factors are conditionally independent of each other (Dahal *et al.,* 2008). For example, a factor map of the geology of the region is overlayed with the landslide inventory and an analysis of the relationship between geology and landslide distribution can be performed. This is repeated for all the factor maps (geology, soil drainage, slope steepness, slope aspect, proximity to faults, land cover, induration and rainfall intensity), and the relative importance of each factor in the control of landslides can be established. The outcome of this bivariate statistical analysis is the produce a set of factor maps with weighting scores for each parameter on the map (Yalcin, 2008). Since the factor maps are analysed separately, the relative importance of factors within a single map (ie, whether granite is more or less susceptible to landsliding than schist for a geology map) is established, but the relationship between the separate maps is not established by this technique.

The original technique of the weighting factor method (Bonham-Carter, 1994) assumes that each factor map (layer) has equal influence on the control of landsliding, so when the various factor maps are overlayed they are given equal weights. Recently, more sophisticated and rigorous techniques have been developed to address the question of what weights to apply to each factor map. One such technique, the analytical hierarchy process (AHP), developed by Thomas Saaty (1978), is a decision tool that can be used to break down complex problems and delivers objective results. It has been applied successfully to landslide susceptibility modelling by many authors (Dai *et al.,* 2001; Komac, 2004; Yalcin, 2008; Liu and Chen, 2003, etc.), and is used in this study to establish the relative importance of the separate factor maps in the control of landslide occurrence. This thesis has trialled both techniques and conducted tests to compare the accuracy of each. The most appropriate technique was then chosen to produce the final landslide susceptibility map.

The weighting factor method of Bonham-Carter (1994) has been used herein to analyse the individual factor maps and establish the weights to apply to each class of each factor map, and the AHP of Saaty (1978) has been utilised to decide on the weights to apply to each factor map. Once these are established, the factor maps are then reclassified using the weighting values, and can then be overlayed in the GIS using the weighted sum tool in ARC GIS 9.3. This produces a landslide susceptibility index (LSI) map, which displays a continuum of landslide susceptibility scores, from very low to very high susceptibility to landsliding.

### 1.4.3 Testing and validation

The predictive power of the resultant landslide susceptibility index map is tested by analysing the success rate (Chung and Fabbri, 2003). This technique plots the cumulative percentage of landslides against the ordered susceptibility values and the area under the curve shows the relative predictive power of the susceptibility map. Since this technique uses the landslide distribution that the susceptibility values were calculated on, it is more of an appraisal of technique than an actual map validation.

To validate the susceptibility map, a new set of aerial photographs was obtained from the Animal Health Board and the landslides visible from these were used in a comparative sense to assess the actual predictive accuracy of the map. The assumption is that the majority of landslides should occur in the higher susceptibility zones.

## 1.5 Development of an historic landslide catalogue

An historical catalogue of landslides in the region was compiled from all the available sources and entries were screened for reliability. For all entries, x,y coordinate pairs were assigned and where possible, 24 hour preceding rainfall amounts were added for rainfall generated landslides and volume estimations made from the descriptions.

The catalogue can then be displayed in a GIS to be used in further classifying the landslide characteristics for a selected area. Interrogation of the catalogue can also be used to put a temporal dimension to the prediction of future landsliding in certain cases.

## 1.6 Thesis structure

This thesis comprises 8 chapters, including introductory and concluding chapters. Chapter 2 introduces the study area. Along with a characterization of the landslide hazard, an outline of the geology, climate and meteorology of the region is provided. A brief overview of the past landslide occurrences and development trends is also presented to give the reader a clear picture of the landslide hazard in the region.

Because a study such as this is limited by the available input data, comprehensive explanations of the landslide inventory, the landslide catalogue and the various thematic data layers are provided in chapter 3.

Chapter 4 explains the process of the weights of evidence modelling (Van Westen, 2003) and subsequent refinement of results using the Analytical Hierarchy Process of Saaty (1978). Also in chapter 4, the process of results testing and validation, using the success rate curve method of Chung and Fabbri (2003), is explained. This leads into the assigning of zones to the final susceptibility map.

Chapter 5 presents the results obtained from the landslide susceptibility modelling and then illustrates the process of comparing a newly mapped dataset of landslides to the landslide susceptibility map. The results of the success rate testing are presented and the validation results are then used to choose the most appropriate maps for use in landslide hazard management in the West Coast Region. This chapter also shows how this data can be used to assign zones to the landslide susceptibility map by placing zonal boundaries that coincide with defined susceptibility values and amounts of actual landsliding observed within each zone.

One of the objectives of this thesis is to provide, and explain the uses of, tools to be used by the local planning authorities to aid in the management of landslide hazard. This is achieved in chapter 6 via a case study of the Waimangaroa to Nikau coastal strip of the Buller District, where landslides are a common and destructive occurrence. It shows how the susceptibility map can be used in conjunction with the landslide catalogue to better define, and ultimately manage, the landslide hazard.

Chapter 7 is a discussion of the data used and the techniques chosen to produce the susceptibility maps. It critically appraises the study and explains its limitations. Suggestions for further research are also presented here.

Chapter 8 is a concluding chapter which summarises and presents the main findings of the thesis.

# Chapter 2. The study area

## 2.1 Geography and population

The study area encompasses the whole of the West Coast Region as defined by the administrative boundary of the WCRC. Within the region there are three districts; Buller, Grey and Westland, with the principal towns in the districts being Westport, Greymouth and Hokitika respectively. It is one of the more sparsely populated areas of New Zealand, with an area of 23,276 km$^2$ and the 2009 population estimated at 32,600 (Statistics New Zealand, 2009). Figure 2.1 shows the study area and its location in New Zealand.

The study area stretches from Kahurangi Point in the north, to Awarau Point in the south, a distance of approximately 600km. It is bounded on the west by the Tasman Sea and to the east are the Southern Alps, a major mountain belt marking the boundary between the Pacific and Australasian tectonic plates. Most of the population resides in the coastal strip of alluvial plains, with the rest of the region being too rugged and inaccessible for sustainable habitation.

Maori traditionally valued the West Coast for its Pounamu, but in the late 1800's gold was discovered close to Greymouth and a brief gold rush ensued. The gold rush was responsible for establishing most of the main towns, and several gold mining operations still exist today. Currently, the main industries are underground and opencast coal mining, alluvial gold mining, dairy farming, forestry and timber processing, fishing and, increasingly, tourism and ecotourism (West Coast Web, 2007). Since mining has been the main industry in the region it follows that residential development has been greatest in close proximity to the mining areas. The settlements of Granity, Ngakawau, Reefton in the Buller district and Greymouth, Rapahoe and Blackball in Grey district all support local mining operations.

Isolated from the rest of the South Island by the Southern Alps, residents of the West Coast have developed a distinctive culture of their own. Their pioneering values of self-reliance and loyalty are a strong indicator of healthy community resilience (West Coast Web, 2007). Historically, residential development has been centred close to mining or forestry work, and more recently, forest clearing and conversion to dairy pastureland has allowed the development of land in the peripheral areas of valleys, and often on elevated alluvial fans.

The West Coast region has a small ratepayer base and in 2003 the sub-national gross domestic product of the region was estimated at $779 million; only 1% of New Zealand's national GDP (Statistics New Zealand, 2007).

For the central and southern areas, the Southern Alps create a geographic barrier to the east, with only 3 road routes connecting the West Coast to the rest of the South Island; Haast Pass, Arthur's Pass and Lewis Pass. In the northern area, the Buller River valley allows access to the rest of the South Island. These routes frequently close due to weather, accidents or landslides, effectively isolating the West Coast region from the rest of the South Island.


**Figure 2.1.** Location map of the study area. Dark green denotes the study area and the West Coast region.

## 2.2 Climate

The West Coast of the South Island is the wettest area of New Zealand, whereas the area to the east of the mountains, less than 100 km away, is the driest (NIWA, 2010).The coastal plains of the West Coast region generally experience mild winters with infrequent frost or snowfall and high rainfall in the spring and early winter. The mountainous areas experience high snowfall during the winter and very intense orographic rainfall at any time, but more commonly in the spring and autumn (NIWA, 2010).

Warm, moist westerly or north-westerly airstreams commonly travel over the Tasman Sea and their moisture condenses upon meeting the Southern Alps. This orographic rainfall can lead to very intense and long-duration rainfall (DTEC, 2002). Mosley and Pearson (1997) described the atmospheric conditions leading to heavy rain as: "*Heavy rains tend to be associated with slow, eastward moving frontal zones embedded in west or nor-west airstreams, where a slow moving anticyclone lies to the north or northeast of the North Island, with a deep depression moving eastwards to the south of the Tasman Sea, and a strong northwest airstream moving ahead of it*".

The interaction of weather patterns and topography has been modelled to produce maps of expected maximum 24hr rainfall during a design rainfall event (Thompson, 2002). Figure 2.2 illustrates the distribution of high intensity rainfall during a 10 year rainfall event in the West Coast region.

From this map it can be seen that the most intense rainfall can be expected in the higher relief areas especially if close to the coast. The model predicts a maximum 24hr rainfall amount of 609mm in the Southern Alps around the Mount Cook area. However, historically recorded rainfall figures have detailed much higher rainfall amounts than this. For example, 800mm of rain was recorded at the Cropp River gauge for a 24hr period from noon on 5$^{th}$ October to noon on 6$^{th}$ October, 1993 (DTEC, 2002).

Annual rainfall figures are similarly high in comparison to other areas of the country and are arguably some of the highest in the world (DTEC, 2002). Figure 2.3 shows the annual rainfall pattern for the region. Data courtesy of NIWA.

Since rainfall is by far the most common trigger for landsliding in the region, a good understanding of the rainfall characteristics and distribution are essential in modelling the expected distribution of landslides.

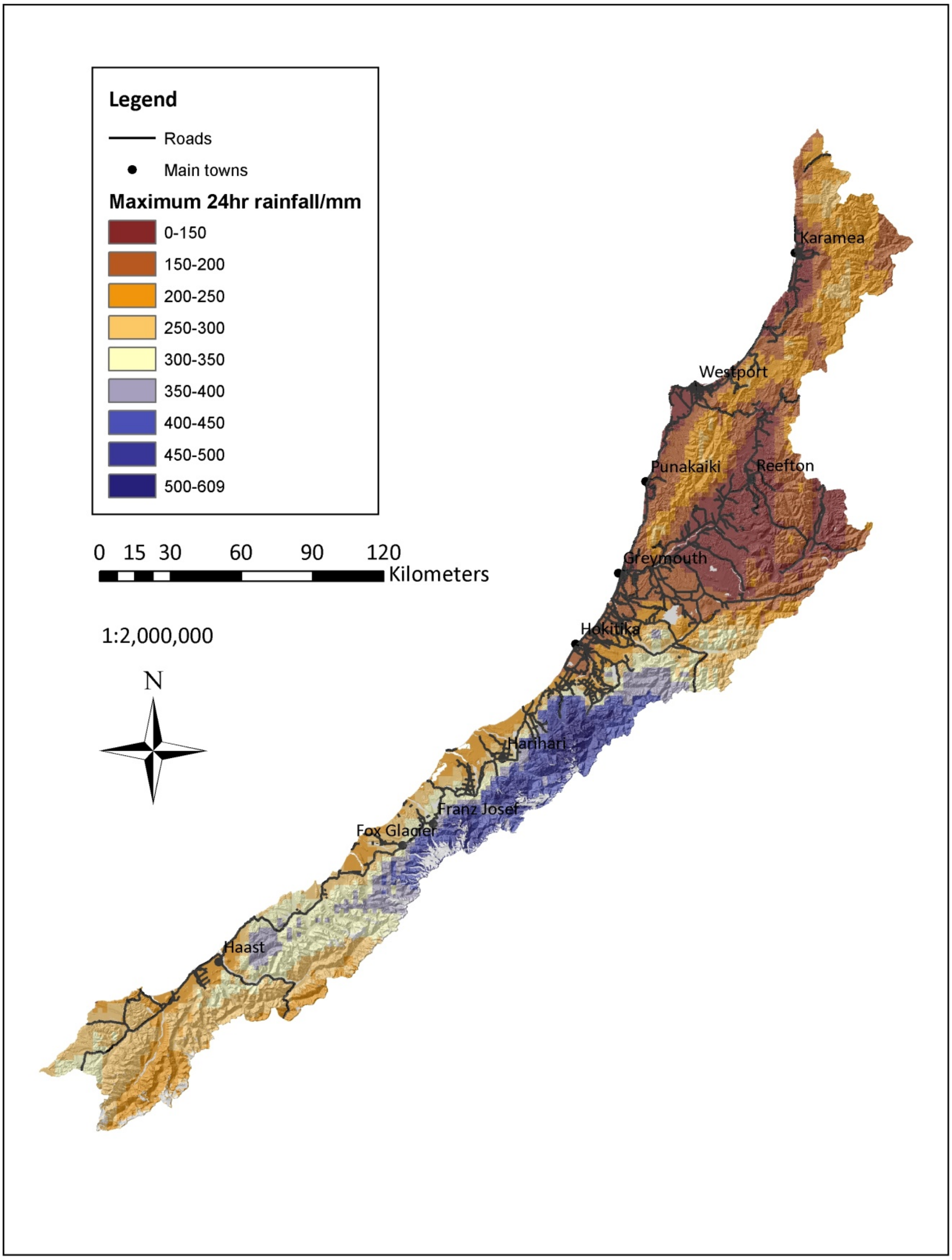



**Figure 2.2.** Modelled 24hr maximum rainfall during a 10 year design rainstorm (data supplied by NIWA).

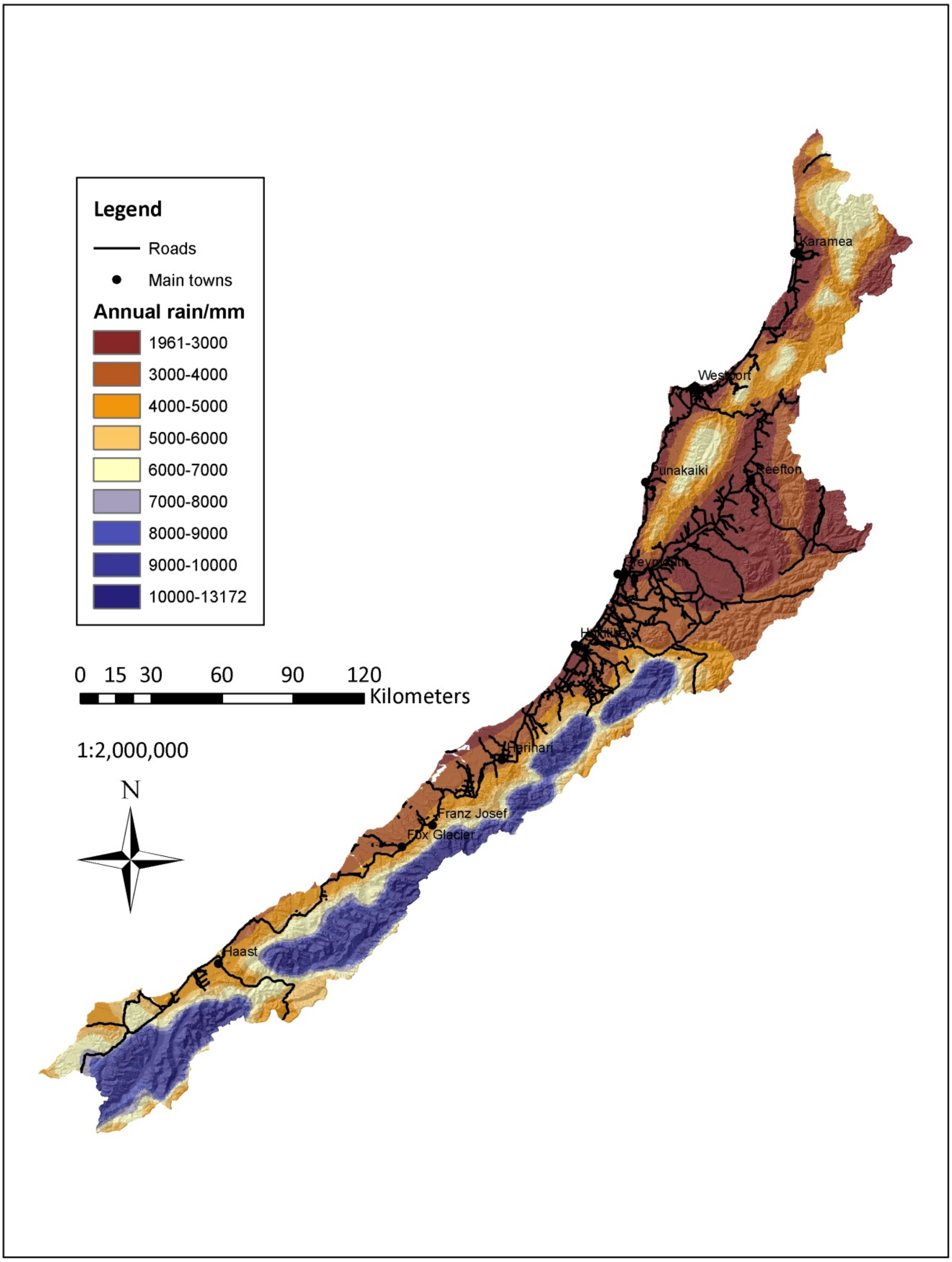



**Figure 2.3.** Annual rainfall map of the West Coast region (Data supplied by NIWA).

## 2.3 Geology

### 2.3.1 Introduction

The Southern Alps of New Zealand form the backbone of the South Island and are the topographic response to active oblique continental convergence of the Australian and Pacific plates (Korup *et al.,* 2005). The plate boundary is marked by the Alpine fault, which shows a horizontal displacement of ~460km, separating the Dun Mountain ophiolite belt in north-western Nelson from its correlatives in Fiordland and Otago (Mortimer, 2008), and effectively dividing the West Coast region into two very distinct geological terranes: rocks east of the Alpine fault and rocks west of the Alpine fault.

Figure 2.4 illustrates the movement along the Alpine fault and the previous alignment of the oldest rocks in the region. The overlying sediments and the schists and greywacke to the east of the Alpine fault are not shown on this map.

To the west of the Alpine fault the oldest rocks in the country are exposed. The Ordovician Greenland series greywackes and argillites form the majority of the basement rocks, which have been intruded by granites in a number of locations (Wellman and Willett, 1942). A series of younger, late Cretaceous and Tertiary sedimentary rocks overlie these and morainic debris from Quaternary glaciations can be observed as hilly ground within the coastal plains (Wellman and Willett, 1942). Great depths of recent sediments derived from the Southern Alps cover most of the western flood plain areas (Thornton, 2003). To the east of the Alpine fault high rates of tectonic uplift have exhumed metamorphic schists of the Haast group (Korup, 2004), which are exposed as mylonites on the hanging wall of the Alpine fault. Metamorphic grade decreases to the east with much of the central Southern Alps composed of highly deformed greywackes (Thornon, 2003).

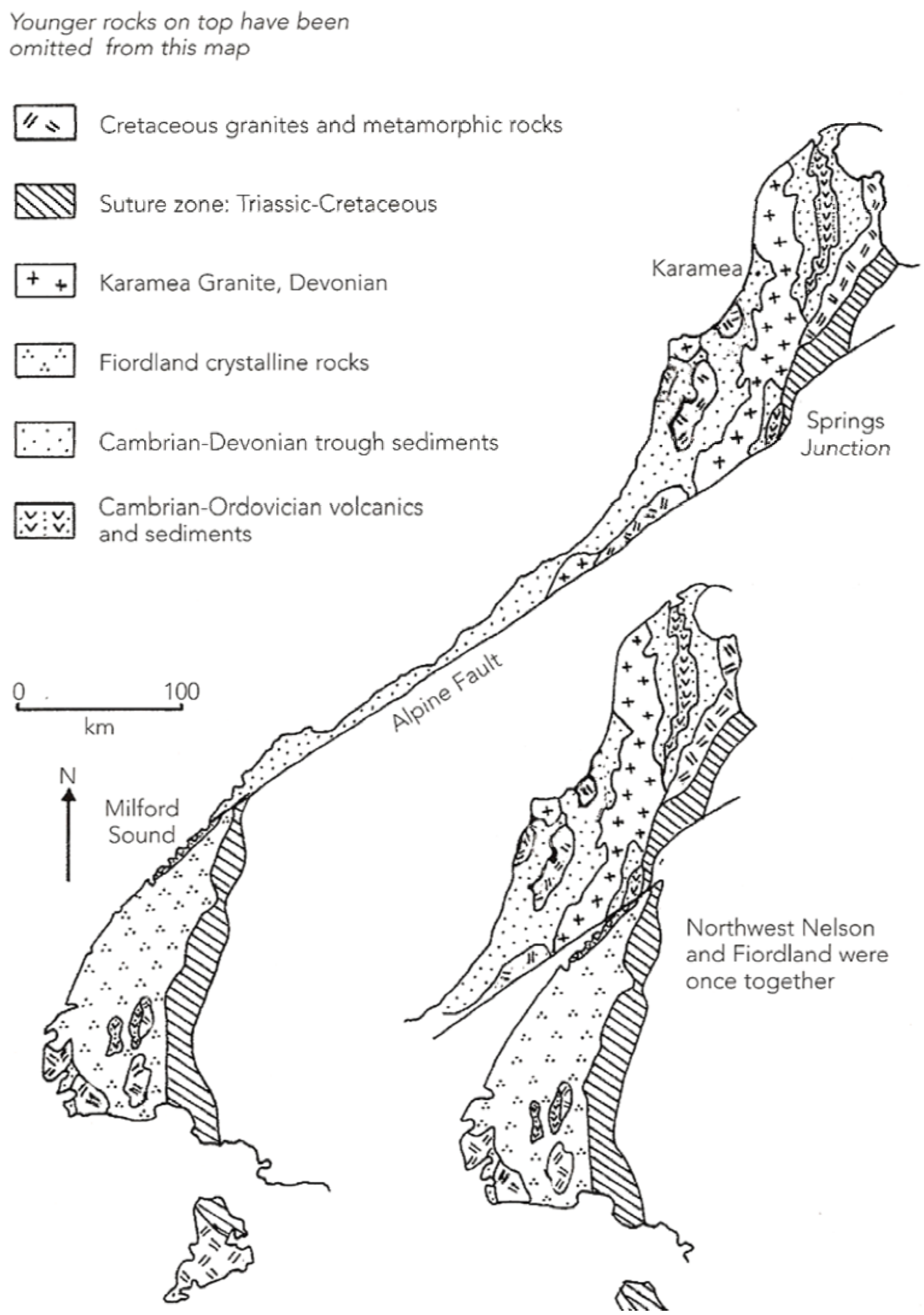



**Figure 2.4.** Displacement of the basement rocks along the Alpine fault. Present day position left, and late Cretaceous (C 65 Ma) position right (from Thornton, 2003).

### 2.3.2 Rocks west of the Alpine fault

The basement Greenland group rocks are a closely folded, westerly-striking series of Ordovician greywackes and argillites, which were intruded by Karamea granites during the Tuhua orogeny in the middle Devonian, ~360 Ma (Thornton, 2003). Although there may be some slight schistosity developed in the far south of the study area, south of Jacksons Bay, the bulk of the alteration has been caused by the contact metamorphism of the granite intrusions. This contact metamorphism has formed localised development of hornfels and spotted schists in most areas (Wellman and Willett, 1942).

Topographically, the granites of the Tuhua orogeny are characterised by isolated beehive-shaped mountains, which are usually partly buried by alluvium. This is illustrated in figure 2.5, which shows a granite intrusion, the Doughboy, which has been partly buried by alluvial gravels of the Hokitika and Kokatahi river valleys.

**Figure 2.5.** The Doughboy, and Mt. Graham in the background, as seen from the Gerhardt Spur Photo: Author

Many of these features are visible in the western part of the West Coast region, with the Turiwhate Range, Island Hill, Mount Tuhua, Mount Graham, The Doughboy, Mount Misery, Doctor's Hill, Bald Hill and Fraser Peak being the best examples. Larger, more expansive exposures of the Karamea Granite are seen in the area inland of Karamea, Cape Foulwind, north Paparoas and east of Reefton. The distribution of the granites and the associated granitoid rocks can be seen in the simplified geological map of the region, figure 2.6.

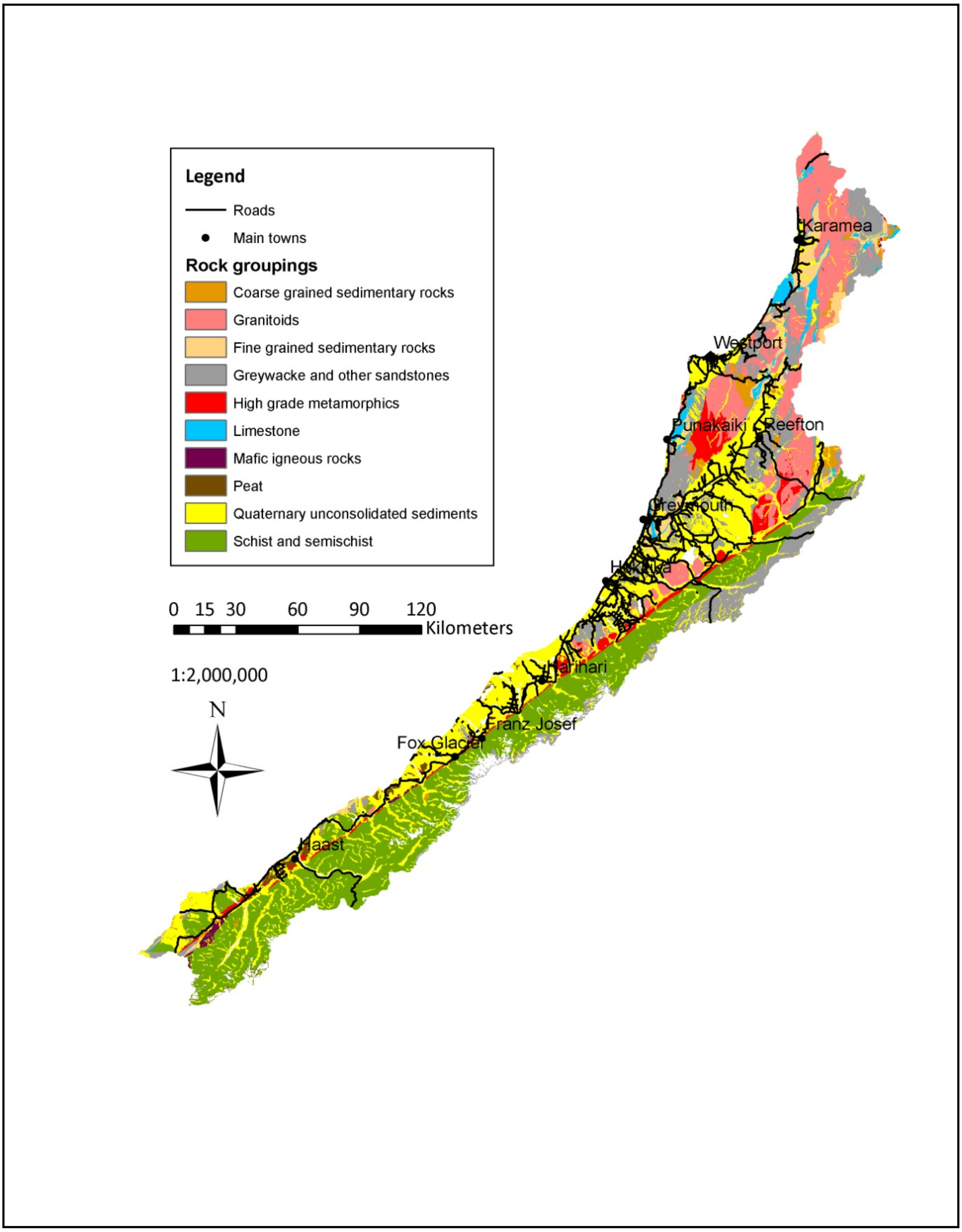



**Figure 2.6.** Simplified geological map of the West Coast region.

Overlying the basement rocks of the western part of the region are a series of Late Cretaceous and Early Tertiary sedimentary rocks which are best developed in the Grey and Buller Districts. This sequence is illustrated in table 2.1.

**Table 2.1.** Stratigraphic summary of the sediments west of the Alpine Fault (from Todd, 1989)

| Formation | Lithology | Age |
|---|---|---|
| Not differentiated | River gravel, marine sand and gravel, dune sand.<br>Raised terraces of river gravel overlying marine sand and gravel | Holocene<br><br>Late Pleistocene |
| | Unconformity | |
| Blue Bottom Group | Massive mudstone and some sandstone up to 1500m thick | Miocene |
| | Unconformity | |
| Whitecliffs Formation | Calcareous mudstone and limestone | Oligocene |
| Kaiata Formation | Micaceous siltstone and mudstone up to 200m thick. Sandy interbeds near the base. | Eocene |
| Brunner Coal Measures | Basal conglomerate, quartzose sandstone, mudstone, shale and coal | Eocene |
| | Unconformity | |
| Karamea batholith | Granite and associated gneiss | Early Cretaceous |
| Greenland Group | Greywacke and argillite, locally metamorphosed to hornfels and schist near the granites | Carboniferous-Permian-Ordovician |

The late Cretaceous Paparoa Coal Measures, made up of repeating sequences of mudstone, sandstone and coal, overlie the basement rocks in the Greymouth area. The Eocene Brunner Coal Measures are much more widespread, extending along the West Coast from south of the Hokitika River to north Buller and east to Murchison (Todd, 1989). The Brunner Coal Measures are generally found to contain a basal conglomerate member, quartzose sandstone, mudstone, shale and at least one very thick coal seam, which has been mined in various locations. Wherever the coal measures are exposed on hillsides, rockfall and landslide occurrences are common, due to the variable erodibility of the strata.

The coal measures are overlain by the shallow marine Kaiata formation, which is generally present as a thick mudstone with a few sandy interbeds near the base. Overlaying the Kaiata mudstone is a thick limestone, which can be seen outcropping at Cobden, Point Elizabeth, Punakaiki, Karamea and at Whitecliffs, in the Buller gorge, from where it takes its name. Typically, the Whitecliffs limestone forms cliffs above the easily eroded mudstones below. These cliffs often present rockfall hazard.

The limestone is unconformably overlain by layers of soft, blue-grey mudstone, which was named the “Blue Bottom” by the early gold miners, who realised that no gold was present below this horizon (Thornton, 2003).

These successions of sediments have been uplifted and faulted by numerous faults. The Kongahu Fault Zone is a zone of major thrust faulting trending South West – North East which forms the western boundary of the uplifted sediments and is the result of post-Oligocene compression (Todd, 1989).

The overlying unconsolidated sediments of Holocene and Pleistocene age have formed thick deposits which in places are visible as raised river terraces. Glacial action during the Pleistocene has left morainic debris in many locations (Chevalier *et al.,* 2009)

### 2.3.3 Rocks East of the Alpine Fault

Bounded to the west by the Alpine Fault, the Southern Alps are the topographic expression of the active oblique compressional boundary between the Indo-Australian and Pacific continental plates. The rapid uplift and thrust of the Pacific plate has exhumed the Haast Schist in the hanging wall which shows localised mylonitization in close proximity to the Alpine Fault (Korup, 2004).

In general, the metamorphic grade decreases with distance from the Alpine Fault. High grade Garnet-Oligoclase schists and Mylonites make up the rocks in contact with the Alpine Fault and grade to the east into the Biotite zone, Chlorite zones and eventually the quartzofeldspathic argillite greywacke close to the main divide (Korup *et al.* 2005). Figure 2.7 shows a simplified cross section of the Southern Alps.

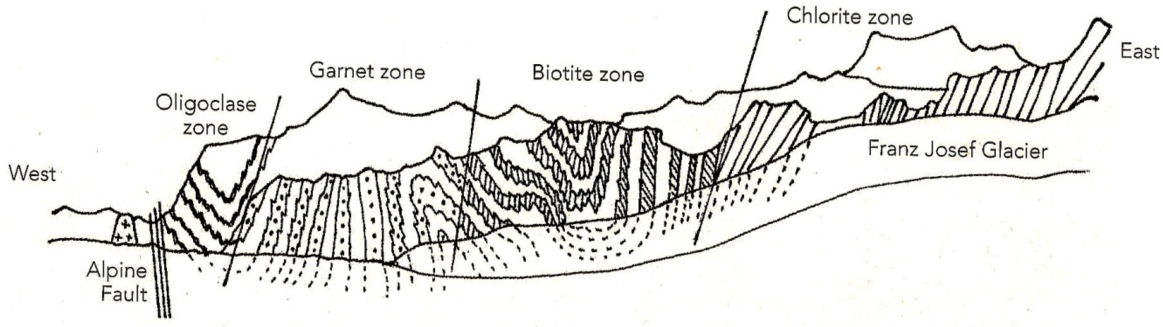



**Figure 2.7.** Cross section showing the zones of metamorphism in the schists of the Southern Alps, as seen at Franz Josef (from Thornton, 2003)

## 2.4 Earthquakes

In recent history, several large earthquakes have occurred in the region. The 1929 Murchison and the 1968 Inangahua earthquakes caused widespread damage and a total of 20 human fatalities (DTec, 2002). Numerous other, smaller earthquakes have occurred in the region due to movements along local faults in the Paparoa Tectonic Zone, the South Westland Shear Zone and the Marlborough Fault Zone. These recent earthquakes are relatively small compared to the pre-historic earthquakes caused by Alpine fault rupture (DTec, 2002).

Wells *et al.* (1999) suggest that the Alpine Fault ruptured about once every 250-260 years causing earthquakes of ~M8 and ground shaking close to the epicentre of MM9-MM10. The most recent Alpine Fault Earthquake has been dated to 1717. Yetton *et al.* (1998) calculated the probability of an Alpine Fault earthquake occurring in the next 50 years as 65% (+/-15%) and in the next 100 years as 85% (+/-10%). The likely magnitude of this event is M8 with the associated ground shaking intensity of MM9-MM10 in the epicentral region (DTec, 2002).

## 2.5 Landslides in the region

Landslides are widespread in the region and since European settlement began in the late 19th century have been responsible for 27 deaths, along with frequent damages to road and rail infrastructure, settlements and agricultural land (Benn, 2005). Rainfall has been shown to be the most common trigger mechanism, being responsible for 90% of all landslides in the region. However, earthquakes have triggered much larger landslides on rarer occasions (Benn, 2005). Landslides triggered by unknown mechanisms (such as the Mt. Cook rock avalanche in 1991, the Mt. Stargazer landslide in 1981 and the Vampire Peak landslide in 2006), are not as common, but are often very large, with millions of cubic meters of rock falling in single events (DTec, 2002). Figure 2.8 shows the debris from the Mt Cook rock avalanche, which was triggered by an unknown mechanism and travelled 7.5km at speeds up to 200km/h, involving over 12,000,000 $m^3$ of rock (Te Ara, 2010).

**Figure 2.8.** The Mt. Cook rock avalanche of 1991. Photo: Lloyd Homer, courtesy of GNS Science (TeAra, 2010).

Most of the previous research on landslides in the region has concentrated on earthquake-triggered landslides (eg. Benn, 1992; Chevalier *et al.,* 2009; Hancox *et al.,* 1998; Whitehouse and Griffiths, 1983; Korup, 2005) and has been almost solely focused on the Southern Alps. Notable exceptions to this are the research that was conducted into the landslides caused by the Murchison and Inangahua earthquakes, which affected the Buller district (Pearce and O'Loughlin, 1985; Lensen and Suggate, 1968) and research on Alpine aseismic landslides by Hovius *et al.* (1997).

Landslide-dammed rivers have been recorded on numerous occasions and have attracted considerable interest from researchers. These landslide dams can fail catastrophically when the water overtops the landslide debris, causing extreme flooding of downstream land, as well as sedimentation and aggradation problems later on (Davies, 2002). Examples include the flooding of Seddonville after the 1929 Murchison earthquake after a landslide dam blocked the Mokihinui River (Pearce and O'Loughlin, 1985), the 1999 Mt. Adams landslide which blocked the Poerua River and caused a flood flow of at least $1400m^3$/second (Hancox *et al.,* 1999, Davies, 2002) and the various landslide dams that have blocked the Callery River upstream of Franz Josef (Davies, 2002).

Large magnitude, low frequency landslide events such as those triggered by earthquakes have affected a much larger area than the smaller, high frequency landslides such as those triggered by rainfall (Korup, 2005). Korup (2005) suggests that large magnitude ($>1km^2$), low frequency landslides constitute up to 83% of the total affected landslide area. However, low magnitude, high frequency landslide events have caused the most property damage, with many of the region's roadways and settlements being repeatedly affected by smaller, rainfall triggered landslides (Benn, 2005).

**Figure 2.9.** Earth slip blocking the Denniston Track road in the Buller district, 18 March, 2007. Photo: Westreef.

Rainfall-triggered landslides in the West Coast region are generally shallow earth-, or debris-slides caused by prolonged or intense rainfall (Hovius *et al.*, 1997). Under certain conditions these can transform into earth or debris flows, which are much faster moving and have longer run-out distances. Figure 2.9 shows a good example of an earth slump, where a shallow failure has deposited soils and the attached vegetation onto a road, which acted as the catch bench for the landslide material. Figure 2.10 shows a debris flow, which damaged property located close to a steep slope. Figure 2.11 illustrates the long run-out capabilities of debris flows, where a mixture of soil, rock and vegetation has travelled at great speed damaging a roadway.

**Figure 2.10.** Property damage caused by a debris flow near Boddytown, 1978. Photo: WCRC archives.

**Figure 2.11.** Debris flow blocking State Highway 6 at 14 Mile Creek, 28 April, 2008. Photo: Mary Trayes, WCRC.

Landslides are a common occurrence in the West Coast region and have become an accepted hazard for many people and communities. This is well illustrated in figure 2.12, which shows recent shallow landslide scars behind the town of Granity, where

**Figure 2.12.** Landslide scars behind the town of Granity, where residents seem comfortable to accept the landslide risk. Photo: DOC.

inhabitants have become accustomed to the landslide hazard and are apparently comfortable to accept the risk.

The surface trace of the Alpine Fault dissects the region and also plays a significant role in the local distribution and type of landslides. Korup (2004), explains that the easily-erodible Schist-derived Mylonites in the Alpine Fault hanging wall are often transported as debris “pulses” from landslides along the Alpine fault and deposited on steep alluvial fans. The resulting catastrophic aggradation on the fans has caused lateral channel instability and increased frequency of flooding and structural damage to bridges and roads on State Highway 6, wherever this is close to the Alpine fault.

Rockfalls associated mainly with the limestone outcrops of the Whitecliffs formation have affected roads and infrastructure on many occasions. These are more often attributed to earthquake or unknown trigger mechanisms than rainfall. Little Wanganui, Punakaiki and more recently, Cobden have all experienced damaging rockfalls from this formation. Figure 2.13 shows the rock debris that fell from the

Cobden Limestone, affecting traffic and damaging the road surface. Fortunately, no casualties resulted from this rockfall.


**Figure 2.13.** The Cobden rockfall, 29 July 2009. Photo: Mary Trayes, WCRC.

## 2.6 Summary

The West Coast region is a sparsely populated area, which is highly prone to earthquake and landslide hazards due to its position on the Alpine Fault. In addition, prolonged periods of rainfall and high intensity rainstorms, often cause flooding and landslides to occur. The Southern Alps act as a geographic barrier, with only three road routes and one rail route connecting the West Coast with the rest of the South Island.

West Coast residential development has been centred around mining communities, which are often close to hilly terrain and are therefore more likely to be prone to landslides. The combination of risk acceptance and poorly informed development planning with regard to natural hazards has led to a situation where many communities and elements of infrastructure are positioned in places that frequently experience landslides.

# Chapter 3. Data collection

## 3.1 Introduction

The accuracy and therefore the eventual usefulness of a landslide susceptibility map are essentially a function of the quality and reliability of the input data. The choice of analysis techniques and the methodology used to process the data are secondary to the actual raw data quality. Poor quality inputs will yield poor results. The data layers required can be divided into three groups; landslide inventory data, environmental factors, and triggering factors (Van Westen *et al.,* 2008). By far the most important dataset is the landslide inventory layer, as this is the layer to which other thematic layers are statistically compared. Achieving a complete inventory of the landslides in a large study area such as the West Coast region is simply not possible. However, every effort has been made to include as many visible landslide scars as possible in an attempt to minimise the introduced error and produce accurate results.

The environmental factors are a collection of thematic layers which are considered to have a controlling effect on the occurrence of landslides and are used as causal factors in the prediction of future landslides (Van Westen *et al.,* 2008).

Environmental factors utilised in this study are:

- Geology (rock types)
- Slope gradient
- Slope aspect
- Land cover
- Soil drainage
- Soil induration
- Proximity to faults

Triggering factors are the factors that eventually cause a potentially unstable slope to fail. By far the most common trigger of landslides in the region is rainfall, followed by earthquake. By definition, a landslide susceptibility map describes the susceptibility of a landscape to landsliding caused by a single trigger (Dai and Lee, 2002), so rainfall and earthquake are considered separately. Since the technique relies on an inventory of landslides generated by a single trigger, it is only possible to accurately model the occurrence of rainfall-generated landslides. The rarity of earthquakes (compared to landslide triggering rainfall events), means that the evidence required to map the extent of earthquake-triggered landslides, simply does not exist, so any attempt to produce an inventory of earthquake-generated landslides will produce incomplete results. Many of the large, prehistoric landslides plotted on the GNS QMAPs are assumed to be triggered by earthquakes, and an inventory based purely on these polygons was used to attempt an analysis of the region's susceptibility to earthquake generated landslides. However, the results obtained were not of sufficient predictive accuracy to be useful. The attempted earthquake generated landslide susceptibility map has been included in appendix C, but should not be used for landslide hazard management.

Understanding the limitations of the input data in terms of scale and mapping parameter roughness is necessary to establish the levels of confidence to apply to the findings and results of the project. One of the criticisms of the weights of evidence method is the high degree of simplification required in the thematic factor maps (Fell *et al.,* 2008). In cases where the classes in a single thematic factor map exceed 10 in number (as in the case of land cover maps) or the data is continuous (as in the case of slope maps), grouping of classes is required. The method of grouping is potentially a source of error, so care is needed to group classes in sensible associations.

The landslide inventory, historic catalogue and all the thematic factor maps are available in appendix A.

## 3.2 Landslide inventory map

As previously mentioned, in order to make a reliable predictive landslide susceptibility map it is crucial to have insight into the spatial distribution of landslides. Information pertaining to the temporal distribution of landslides is essential for the generation of hazard maps, as these are designed to give a probability of occurrence in a given timeframe (Van Westen *et al.,* 2008). The regional scale of this project combined with the availability of suitable data precludes the possibility of producing a regional hazard map. The inventory used here does not define the timeframe of occurrence, thus limiting the output to a susceptibility assessment (Fell *et al.,* 2008).

Nevertheless, every effort has been made to map as many visible landslides as possible. The best method of identifying and mapping landslides is the interpretation of stereoscopic pairs of high resolution aerial photographs. Unfortunately, the high cost of obtaining high resolution aerial photography for a study area of this size has necessitated the use of multiple sources of imagery with differing resolutions and quality.

The aerial photography archive held at the West Coast Regional Council offices in Paroa formed the main input to the landslide inventory map. Figure 3.1 shows the coverage of high resolution aerial photography available for use in this study. The areas of highest interest to WCRC are the most heavily-populated areas and areas where resource and building consents are granted, so much of the less-densely populated areas are not covered by this aerial photograph dataset.

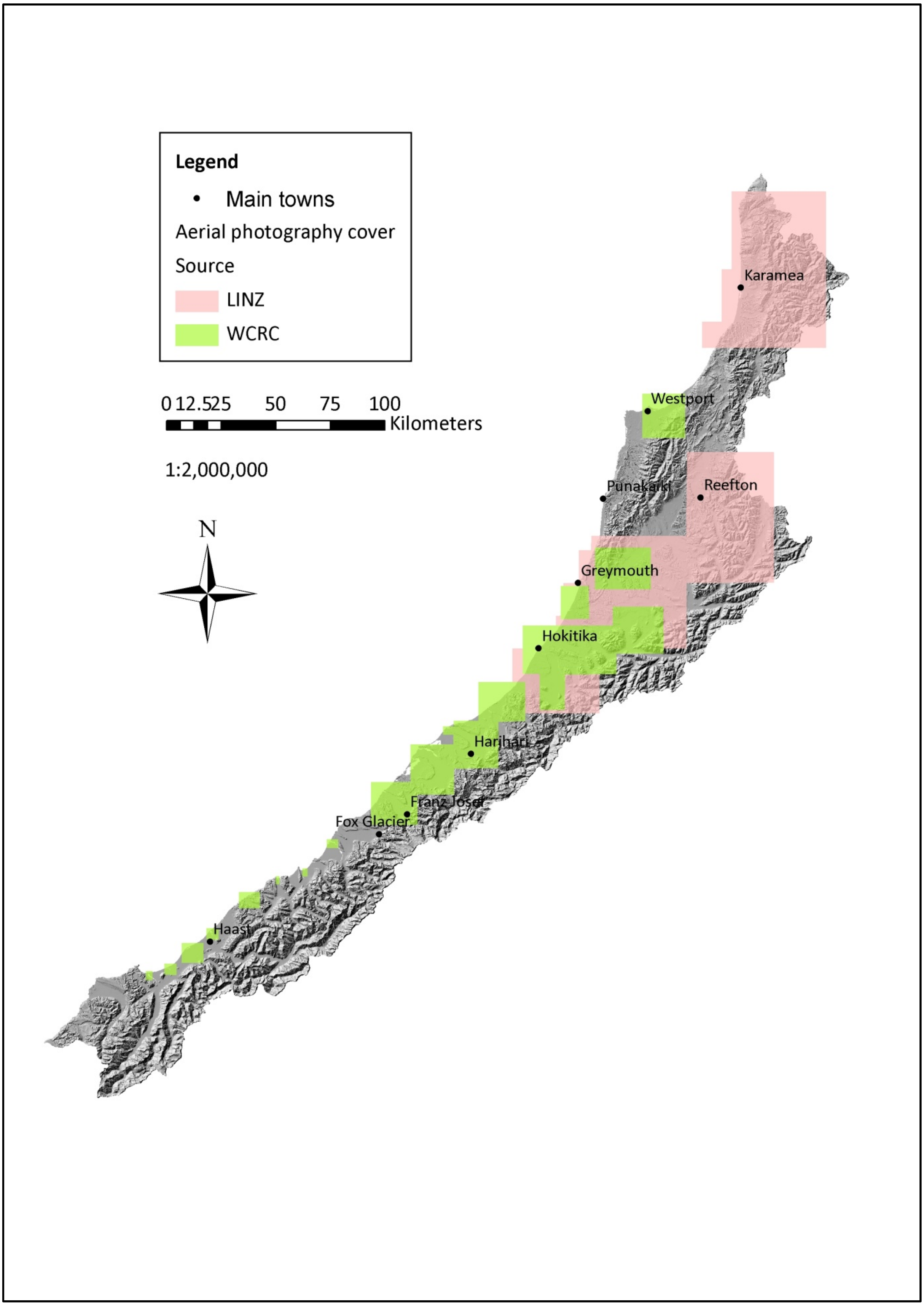



**Figure 3.1.** Coverage of aerial photography used for landslide mapping. Pink areas show photography obtained by Land Information New Zealand (LINZ) and green areas show photography obtained by WCRC. All photo's stored at WCRC.

Landslides are most often identified by spotting disturbed or absent vegetation cover and can often be digitised into a GIS directly from orthorectified digital aerial photography. Figure 3.2 shows a digital aerial photograph from Kahurangi National Park, in north Buller District. The absence of vegetation is a clear indicator of the presence of a landslide. However, the revegetated slopes in the area may also represent landslide scars, but the certainty of identification is not as great. This illustrates the subjectivity of aerial photograph interpretation (API) and exemplifies the need for periodic field checking of digitised landslides to assess the accuracy of interpretation. In cases where the identification of a landslide is questionable, it was decided that it should not be included in the inventory.

Various problems are encountered in API:

- Southerly-aspect slopes are often shaded, depending on the time of day when the photograph was taken. This makes observations of these slopes difficult and some landslides on these slopes may not be recorded.
- Very steep slopes as are observed in the western range-front areas may obscure landslide scars.
- Small debris flows may not be visible as dense vegetation cover in mature forest is often left intact, or regenerates fast enough to hide the landslide.
- Differentiation of source and deposit areas is usually not possible from API alone, so a generalised outline of the affected area of the landslide is the best that can be produced.

Despite these drawbacks API is still the most reliable and efficient method of identifying landslides in large study areas (Van Westen *et al.,* 2008).

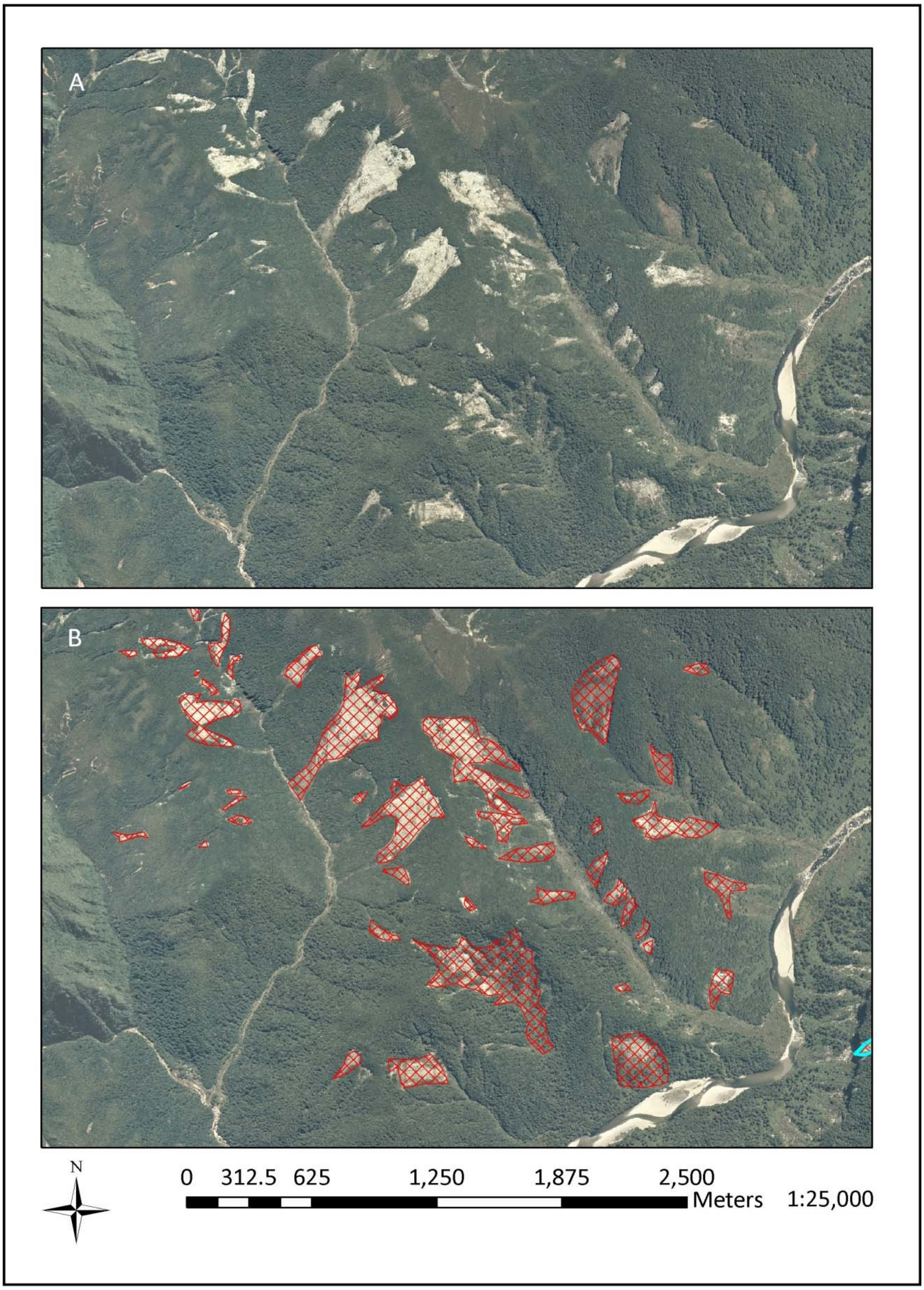



**Figure 3.2**. Example of the use of aerial photography in identifying landslides. Image A shows a 1:25,000 image from Kahurangi National Park, north Buller District. Image B is the same area with landslides digitized.

In areas outside of the aerial photography coverage, it was possible to identify some landslides from satellite imagery available from Google Earth. Only large features (>50m width) were reliably identified by this means. An extensive oblique aerial photography dataset was obtained from the Department of Conseravtion in Hokitika, which provided another means of identifying landslides. Accurate georeferencing was not possible, so the subsequent mapping from these photographs was correspondingly approximate. However, the benefit of including these landslides in the study outweighs the problems associated with inaccurate mapping, so it was decided to include the landslides mapped by this means. The approximate accuracy of this form of landslide mapping is +/-50m. Figure 3.3 shows an example of the landslides mapped by this means.

**Figure 3.3.** Landslides visible from oblique aerial photography in Granity, Buller District (Photo: DoC).

Direct observations from the ground were used to verify the landslides identified from API and map other landslides in areas where aerial photography was not available. During a spell of particularly fine weather, an observational field trip was conducted. In order to observe as much of the region as possible, a trip was planned that encompassed a route including the northern extent of the region as far as the road end at Kohaihai, 15km north of Karamea, and the southern extent of the region as far as the road is drivable at the Cascade River. Arthur’s Pass and the Lewis Pass were also driven, but weather prevented any useful observations in the Haast Pass.

This route is illustrated in figure 3.4. The purpose of this trip was twofold. Firstly, the positions of landslides digitized from vertical and oblique aerial photography could be verified (using hand-held GPS) and an accuracy assigned these methods of mapping. Secondly, any notable landslides that had not already been included in the inventory could be mapped in the field. Due to time constraints and the regional scale of the mapping it was decided that mapping from a distance was an acceptable means of recording a landslide's position. The accuracy of landslides digitized by this means is +/-100m. Landslides were observed and mapped from distances as great as a few km, which is potentially a source of error. As previously explained for the case of landslides observed from oblique aerial photography, the benefits of including these inaccurately mapped landslides far outweighs the problems associated with accuracy of mapping, so landslides that were observed from the ground were included in the inventory if reasonable observations were possible.

Landslides mapped by other observers were not used in this study with the exception of landslides included in the GNS GMAPs. 668 landslides mapped by various researchers have been extracted from the 6 QMAPs for the region and included in this study. The majority of these features are prehistoric earthquake-(or other mechanism) triggered landslides, which have been mapped in the field.

The landslides were divided into two classes: rainfall-triggered and earthquake-(or other mechanism) triggered. Often, assumptions based on size and age were made during this classification, whereby a fresh landslide scar which has affected only surficial materials will be classified as rainfall-triggered, and much larger, deep-seated movements are classified as earthquake-(or other mechanism) triggered. In many cases, the information from the historic catalogue of landslides can be used to classify mapped landslides.

In total, 2566 rainfall-triggered landslides with a combined area of 61.4 km$^2$ and 522 earthquake-(or other mechanism) triggered landslides with a combined area of 497.9 km$^2$ were mapped and this makes up the landslide inventory dataset.

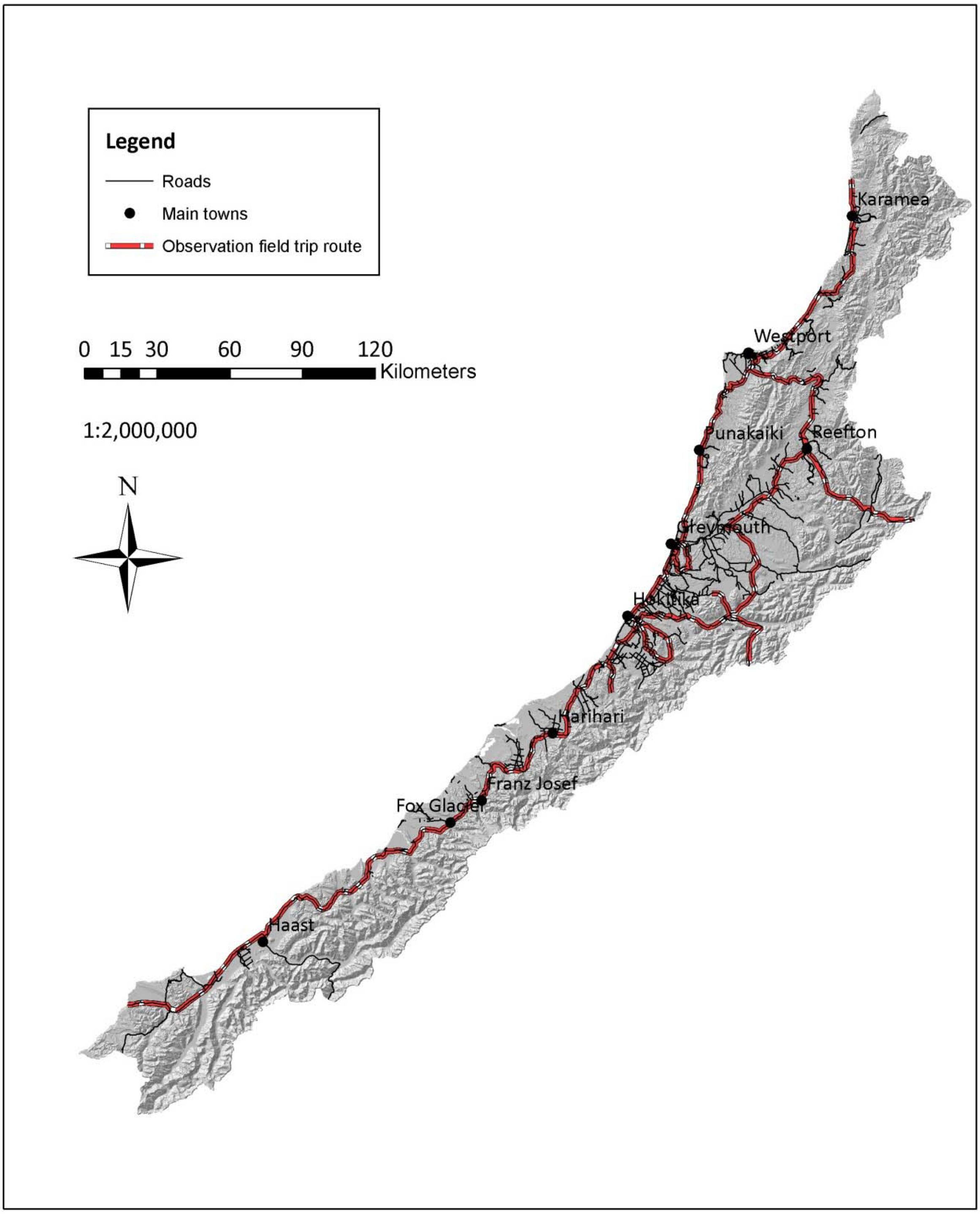



**Figure 3.4.** Illustration of the route taken during the observational field trip.

## 3.3 Thematic factor maps

Eight thematic factor maps were chosen, representing the factors assumed to be the most important in the control of landslides in the West Coast region. These are described below.

### 3.3.1 Geology

Since the QMAP project began in 1994, GNS Science has produced a series of geologic maps for New Zealand. This Crown-funded research program will produce a seamless regional scale (1:250,000) digital geologic database covering the whole country (GNS Science, 2010). These digital maps provide the most reliable source of geological information available, so were used in this study. Licensed copies of the required published maps were available through the WCRC and the Geological Sciences Department. Additionally, unpublished data from the Haast and Aoraki QMAP sheets were made available and obtained directly from Simon Cox at GNS Science.

The geologic units contained within the 6 QMAP sheets for the West Coast Region (Nelson, Greymouth, Kaikoura, Aoraki, Haast and Wakatipu) were imported into a GIS and extracted to produce a regional geology map. The resulting 45 rock types were then grouped into the classes described in table 3.1.

**Table 3.1.** Geological groupings used in the regional geology map.

| Raster class name | Main rocks from the GNS QMAPs |
|---|---|
| (1) Quaternary unconsolidated sediments | Boulders, gravel, sand, silt, till. |
| (2) Coarse grained sediments | Breccia, conglomerate, melange. |
| (3) Fine grained sediments | Calcareous mudstone, mudstone, siltstone, shale, tuff. |
| (4) Granitoids | Tonalite, granite, granodiorite, monzodiorite, monzogranite, diorite, quartz diorite, andesite. |
| (5) Mafics and ultramafics | Peridotite, dolerite, gabbro, basalt, amphibolite. |
| (6) Medium grained sediments | Argillite, quartzite, sandstone, volcanic sandstone. |
| (7) Low to medium grade metamorphics | Greenschist, schist, semischist, serpentinite, metapelite, metapsammite, metasandstone. |
| (8) High grade metamorphics | Hornfels, mylonite, orthogneiss, paragneiss. |
| (9) Limestone | Limestone. |
| (10) Peat | Peat. |

### 3.3.2 Slope gradient

Slope steepness, or gradient, has long been recognised as the principal controlling variable in gravitational slope movements (Crozier, 1986; Cruden and Varnes, 1996, Van Westen *et al.*, 2008). Slope gradient maps can be generated quite simply from a digital elevation model (DEM) within a GIS.

The DEM used in this study was prepared for the Foundation for Research, Science and Technology in 2002. Land Information New Zealand provided Landcare Research with photogrammetrically derived 20m contours, spot heights, lake shorelines and coastlines, which was then used to generate a 25m cell size DEM using Landcare Research's internally developed software as described in Barringer *et al.* (2002). The resultant DEM was checked for accuracy by comparing it to a very high resolution LIDAR-derived DEM with results showing that errors are confined predominantly to valley floors, and the overall root mean square (RMS) error of 8.15 meets the internationally-accepted accuracy standards set out by the US Geological Survey. This DEM is available as a commercial product and was used for this study under licence for research purposes only at the University of Canterbury, Department of Geological Sciences.

The slope gradient map was generated, using the same grid cell size of 25m, and then reclassified into the following slope classes: (1) 0-10˚, (2) 10-20˚, (3) 20-25˚, (4) 25-30˚, (5) 30-35˚, (6) 35-40˚, (7) 40-45˚, (8) 45-50˚ and (9) 50˚+.

### 3.3.3 Slope aspect

The same DEM as described above was used to generate a slope aspect map, which was conveniently reclassified into the following slope aspect classes: (1) flat (no aspect), (2) north, (3) north-east, (4) east, (5) south-east, (6) south, (7) south-west, (8) west and (9) north-west. For consistency, a 25m grid cell size was used.

### 3.3.4 Land cover

The New Zealand Climate Change Office and the Ministry for the Environment publish a Land Cover Database which is a thematic classification of 43 land-cover and land-use classes in New Zealand. It primarily uses SPOT 5 and Landsat 7 satellite imagery to identify the different land-cover classes. The first Land Cover Database

(LCDB1) was completed in 2000 and the second (LCDB2) was released in 2004, and was intended as a formal method of tracking climate change related land-use/land-cover changes (New Zealand Climate Change Office, 2002). This study uses LCDB2 under licence from WCRC.

The spatial resolution of the Landsat 7 images used to produce LCDB2 is 15m, but the positional accuracy is as much as 60m in areas of few ground control points, so it is designed to be used at a scale of no larger than 1:25,000.

The land use classes have been grouped into the classes described in table 3.2

**Table 3.2.** Land cover classes used in the land cover thematic map.

| Land cover class | LCDB2 land cover classes |
|---|---|
| (1) Exotic forests | Deciduous Hardwoods/ Other Exotic Forest/ Major Shelterbelts/ Pine Forest – Closed Canopy/ Afforestation (not imaged)/ Forest Harvested/ Pine Forest – Open Canopy/ Afforestation (imaged, post LCDB 1)/ Vineyard/ Orchard and Other Perennial Crops |
| (2) Freshwater and saline vegetation | Herbaceous Freshwater Vegetation/ Herbaceous Saline Vegetation |
| (3) Infrastructure | Built-up Area/ Surface Mine/ Urban Parkland/ Open Space/ Transport Infrastructure/ Dump |
| (4) Indigenous forests | Indigenous Forest/ Broadleaved Indigenous Hardwoods/ Manuka and or Kanuka |
| (5) Alpine areas | Sub Alpine Shrubland/ Alpine Grass-/Herbfield/ Alpine Gravel and Rock |
| (6) Mixed shrublands | Grey Scrub/ Flaxland/ Fernland/ Gorse and Broom/ Mixed Exotic Shrubland |
| (7) Pasture land | Low Producing Grassland/ High Producing Exotic Grassland/ Short-rotation Cropland |
| (8) Tussock grasslands | Tall Tussock Grassland/ Depleted Tussock Grassland |

Land-cover classes that do not relate to landsliding were removed from the map, so areas of open water, coastal sand and gravel, river bed gravel, etc have been excluded from the landslide susceptibility assessment.

Similarly, areas of permanent snow and ice have been removed from the land-cover thematic factor map. This was done because these areas are subject to a very different set of rules governing landscape stability, and this thesis makes no attempt to classify snow and ice avalanches, or glacial collapse.

Areas of the map that were classified as "landslide" were dealt with individually, and an attempt was made to identify the original land-cover before the landslide occurred. To do this, the LCDB1 was referred to and if the landslide had occurred after the imagery for LCDB1 was collected the original land cover was described here. If the landslide occurred before LCDB1, then the surrounding land cover class was assumed to be the original land cover class before the landslide occurred. In cases where more than 1 class surrounds the landslide polygon the upslope land cover was used. For example, observation of a landslide that occurred in alpine tussock and broad leaved indigenous forest, would reveal that the landslide was initiated in the alpine tussock (upslope of the indigenous forest), so the landslide polygon was then reclassified as alpine tussock.

### 3.3.5 Soil drainage

Land Environments of New Zealand (LENZ) is a land classification system designed by Landcare Research, Ltd. with the underlying data layers being available for research purposes as described in Leathwick *et al.* (2003). It uses the New Zealand Land Resource Inventory and the New Zealand Soils Database, in combination with field mapping to derive values of soil properties on a national scale. The accuracy and reliability of the mapped soil values is very variable due to the small mapping scales (1:250,000), and the poor availability of measured soil properties. However, it is clear that a measure of soil drainage is useful in the prediction of rainfall-triggered landslide occurrence, so it was decided to use the LENZ soil drainage map in this study.

The soil drainage layer of the LENZ classification describes the internal drainage of the soils and divides soils into the classes described in table 3.3.

**Table 3.3.** Soil drainage classes.

| Soil drainage class | Diagnostic criteria |
|---|---|
| (1) Very poor | Having an organic horizon with pale colours due to water-logging in the horizon immediately below |
| (2) Poor | Have pale colours due to water-logging immediately below the topsoil |
| (3) Imperfect | Have pale mottled colours due to water-logging at intermediate depths in the subsoil |
| (4) Moderate | Have pale mottled colours due to water-logging at lower depths in the subsoil |
| (5) Good (well drained) | Lacking significant mottling or pale colours |

This study uses the LENZ soil drainage layer under licence from WCRC.

### 3.3.6 Soil induration

The LENZ data layers also contain information relating to soil induration. The same limitations are encountered with this layer as with the soil drainage layer, but the usefulness of including it in this study was similar. It has been included for use in this study.

It classifies the soils into the classes described in table 3.4.

**Table 3.4.** Soil induration classes.

| Soil induration class | Definition |
|---|---|
| (1) Non-indurated | A specimen disaggregates or slakes within one hour when placed in water |
| (2) Very weakly indurated | A specimen does not slake in water, but can be crushed with the thumb and forefinger when wet |
| (3) Weakly indurated | A wet test specimen cannot be crushed with the thumb and forefinger, but fails when subjected to average bodyweight applied slowly with one foot |
| (4) Strongly indurated | A wet test specimen can only be broken when struck a sharp blow with a hammer |
| (5) Very strongly indurated | Cannot be broken when struck a sharp blow with a hammer |

This study uses the LENZ soil induration layer under licence from WCRC.

### 3.3.7 Proximity to faults

Many authors have noted the correlations between faulting and the distribution of landslides (eg. Korup, 2004). Since the intensity of fault-related rock fracturing in the zone around a fault decreases with distance from the fault, proximity to a fault is a good indicator of rock mass strength (Sarkar *et al.,* 2008). Because of this, the use of buffer zones around faults has become standard practice for statistical landslide predictive studies (Van Westen *et al.,* 2008).

The faults plotted on the 6 QMAP sheets for the region were extracted to form a regional fault map. Buffers of 100m, 1000m and 3000m were applied to all the faults, thus dividing the region into 4 classes: closer than 100m to a fault, between 100m and 1000m to a fault, between 1000m and 3000m from a fault and over 3000m from a known fault.

### 3.3.8 High intensity rainfall

As landslides are usually triggered by heavy rainfall a map of maximum expected rainfall in 24 hours for a specific return period rainstorm is more useful than a traditional annual rainfall map (van Westen *et al.,* 2008). Fortunately, Craig Thompson of the National Institute of Water and Atmospheric Research (NIWA) developed the High Intensity Rainfall Design System (HIRDS), which is a computer-based procedure for estimating design rainfalls in New Zealand (Thompson, 2002).

Since much of the input rainfall data for the HIRDS model was provided by the Regional Councils (including WCRC) throughout New Zealand, the model was made available to WCRC and this study has used a HIRDS model which illustrates the maximum rainfall expected during a 10 year design rainstorm.

The map was received in a continuous raster format, so it was reclassified into the following classes of 24 hour maximum rainfall in a 10 year design rainstorm: (1) 0-150mm, (2) 150-200mm, (3) 200-250mm, (4) 250-300mm, (5) 300-350mm, (6) 350-400mm, (7) 400-450mm, (8) 450-500mm, (9) 500-609mm.

## 3.4 Raster data preparation for weights of evidence modelling

In order to allow statistically robust comparisons between the various factor maps and the landslide distribution, each of the 8 thematic factor maps described above were prepared in the following manner:

- Firstly, all vector based maps were converted to raster format. Since the DEM used to generate the slope gradient and aspect maps was composed of 25m grid cells, or pixels, all the other raster maps were also converted to 25m grid cells. Care was taken to ensure that all rasters were spatially aligned.
- Secondly, an outline polygon map of the study area was prepared, which covers the whole of the West Coast Region as defined by the Regional Council administrative boundary. Areas that were not to be included in the analysis, such as permanent snow and ice, lakes, rivers, estuaries, coastal sand and gravel and river bed gravels and rock were extracted from the regional outline polygon
- Finally, this polygon was used as a mask to extract the same areas from each of the thematic factor maps, producing equally-sized and aligned raster data layers.

Figures 3.5, 3.6, 3.7 and 3.8 are examples of the raster maps created for each of the data layers.

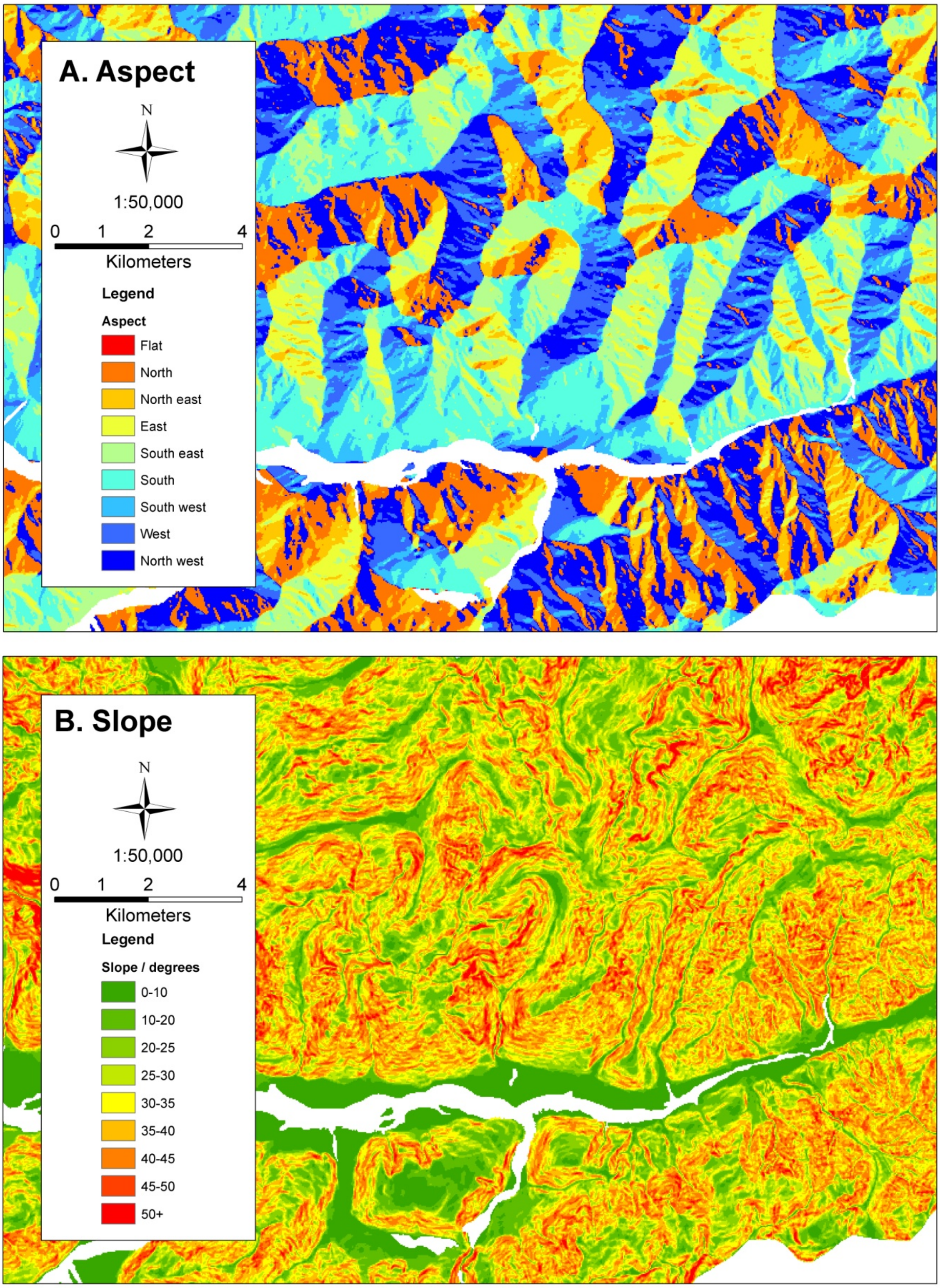
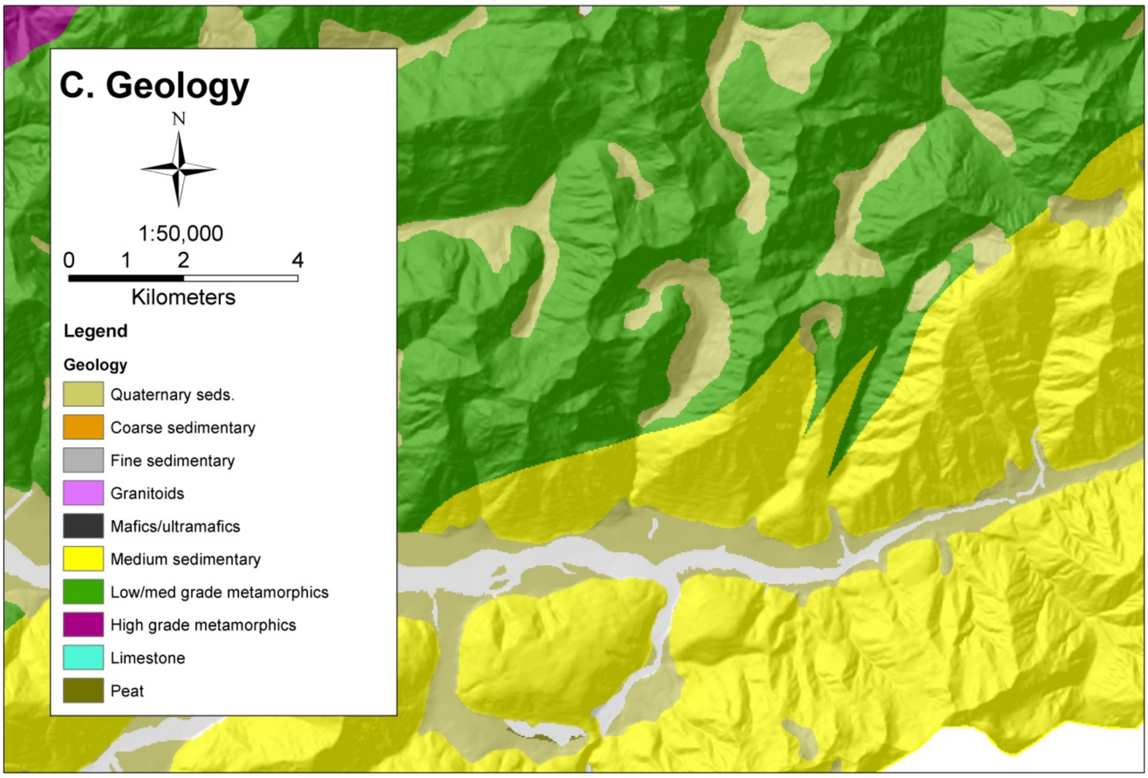



**Figure 3.5.** Example raster maps of aspect and slope.



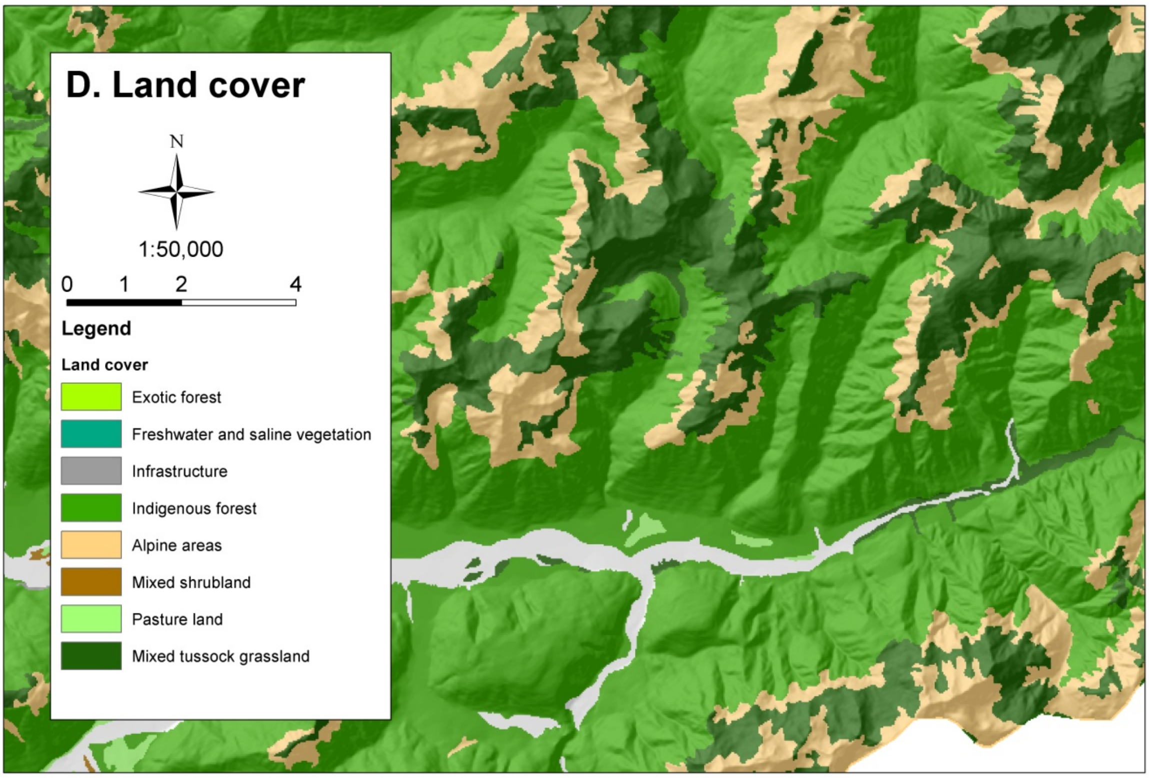




**Figure 3.6.** Example raster maps of geology and land cover.

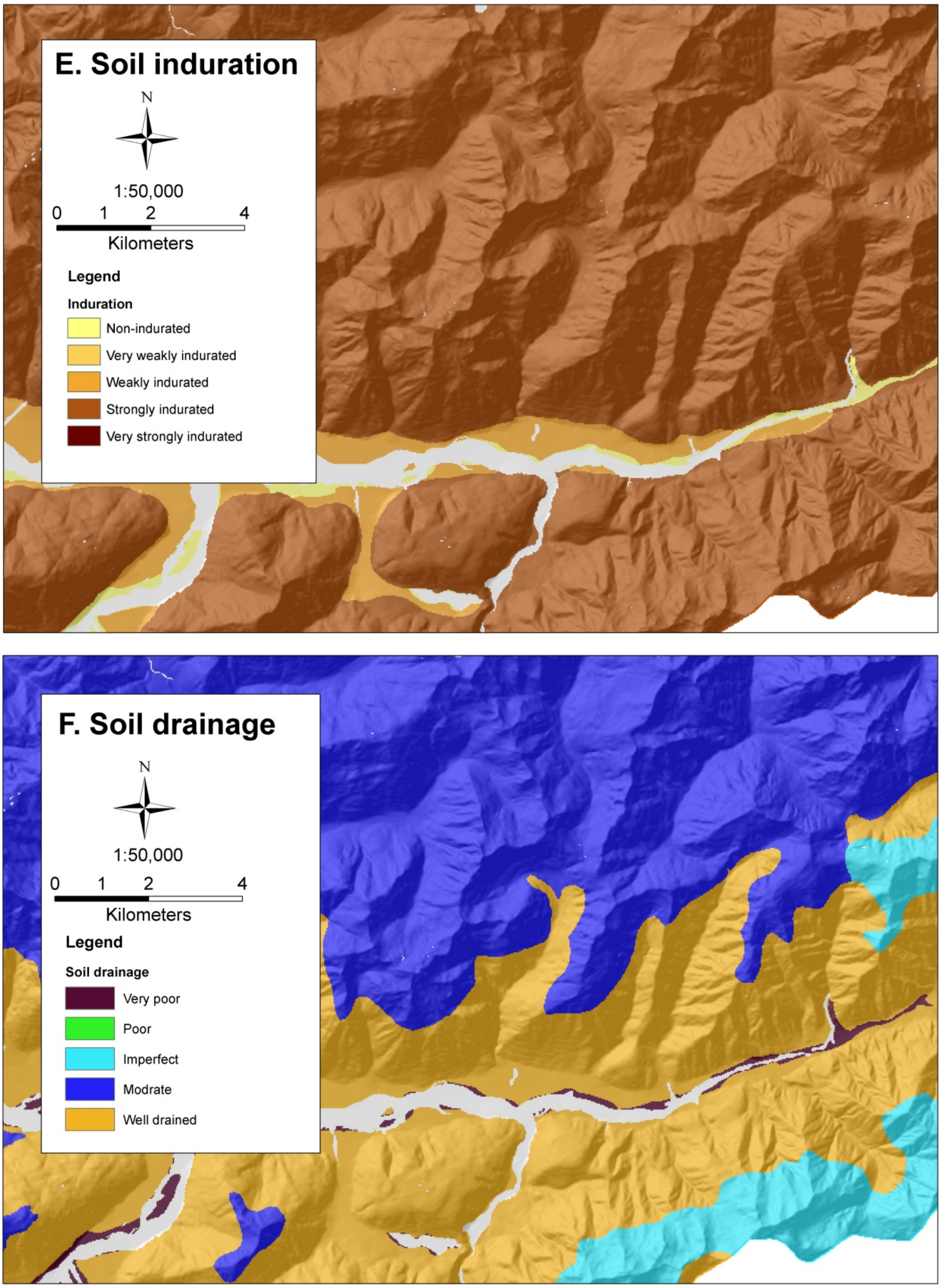
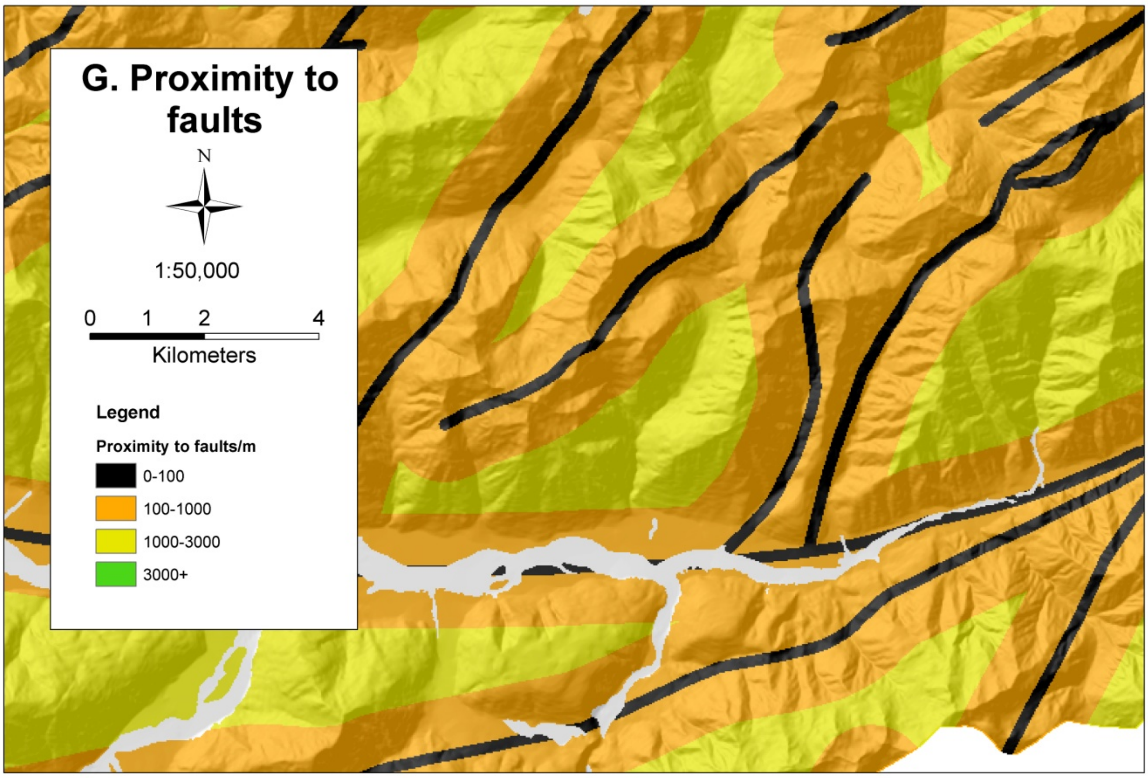



**Figure 3.7.** Example raster maps of soil induration and soil drainage.



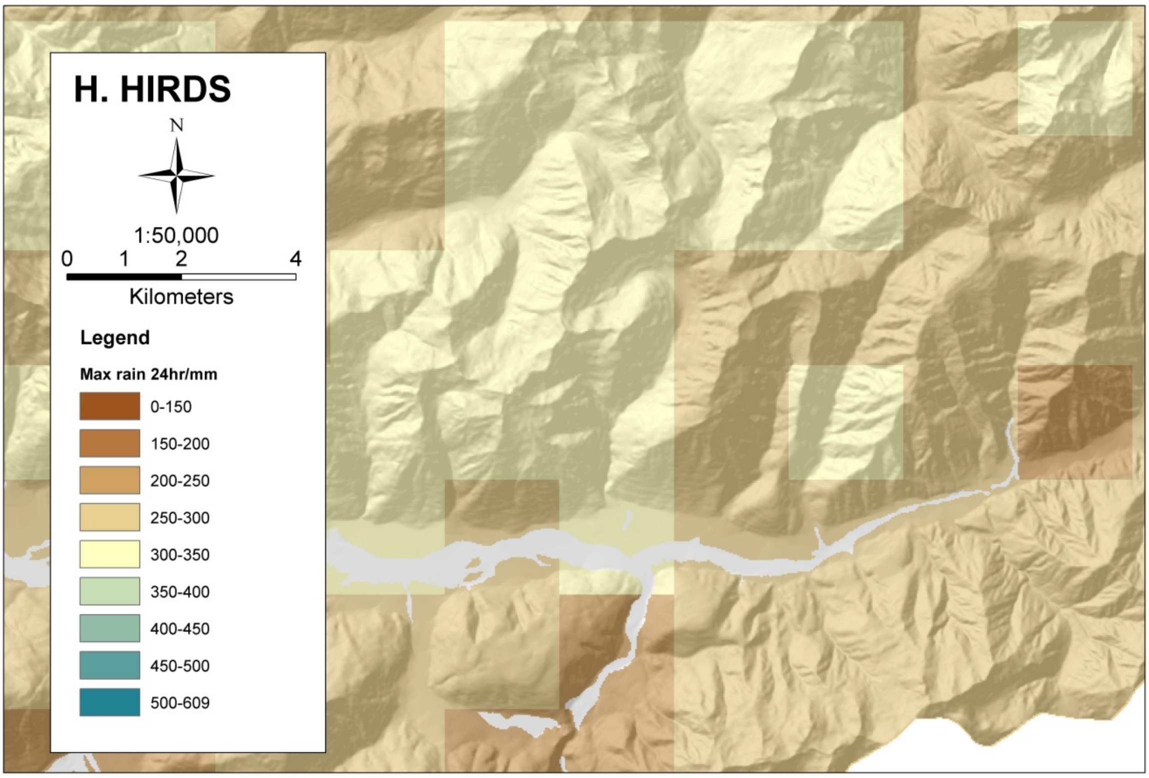




**Figure 3.8.** Example raster maps of proximity to faults and rainfall intensity.

## 3.5 Limitations of the data layers

The range of factors that contribute to the landscape's susceptibility to landsliding is much greater than the factors described above. However, the data availability and the regional scale of this study limit the use of additional data layers.

Notably, the relationship between the orientation of rock mass defects such as bedding planes or schistosity to the orientation of the ground surface has been shown to have a direct bearing on landscape stability (Bell, 1994). Where bedding or schistosity is parallel or sub-parallel to a hillside the stability of that hillside may be compromised. Structural information on the orientation of these geologic features is available, so an attempt was made to quantify this and delineate landslide susceptibility based on these observations. Extrapolation between the sparse data points leads to local inaccuracies, so it was decided that this landslide causal factor should not be used in this study. As noted by Fell *et al.* (2008) and Van Westen *et al.* (2003), the use of structural data in the prediction of landslide susceptibility or hazard studies should be restricted to larger-scale or site-specific studies, where many data points can be collected and used to accurately model the geological structures of the site.

Many landslide susceptibility or hazard mapping studies use proximity to streams as a predictor for future landsliding. By placing buffers around first and second order streams a correlation can sometimes be established with the landslide distribution. This was also attempted in this study, but the results were not conclusive. No correlation was found between the stream locations and the landslide distribution. The reasons for this are twofold: firstly, landslides initiated in close proximity to streams are usually triggered by erosive action of the stream on the toe of the slope, and this study attempts to delineate the distribution of landslides triggered by rainfall, not river or stream bank erosion. Secondly, when mapping landslides from aerial photography, a landslide that has been initiated close to a stream and terminated in the stream bed may not be visible on the aerial photograph. For these reasons proximity to streams was not included as a causal factor in this study.

The highest resolution DEM available is a 25m grid and was used to generate two of the factor maps, namely aspect and slope. This 25m grid resolution effectively limits the resolution of the final susceptibility maps to this 25m grid size.

The scale of the original maps used to generate the raster maps varies and this has effects on the resolution of the raster and the coarseness of the data it represents. For example, the HIRDS map shown in figure 3.8 (H), is the output of a national scale high intensity rainfall model, which uses a grid resolution of 2km, so whilst this map has been rasterized to display 25m grid cells, the underlying data has a coarseness of 2km.

In addition to the scale issues, many of the data layers described above are outputs of models, based on calculations of parameters and extrapolations of (sometimes sparse) data points. The accuracy of the models was not independently tested during this study, so the degree of uncertainty and the amount of introduced error from the input models is not accurately known.

## 3.6 The historic landslide catalogue

An historic landslide catalogue was compiled using the existing catalogues as described in table 3.5. For all entries, x,y coordinate pairs were assigned and where possible, 24 hour preceding rainfall amounts were added for rainfall-generated landslides and volume estimations made from the descriptions.

**Table 3.5.** Existing landslide catalogues used in this study**.**

| Study/source | Geographic area | Dates | Sub-sources | Comments |
|---|---|---|---|---|
| Smith, 2004. | Otira-Arthur's Pass to Jacksons on SH73. Taramakau valley- Jacksons to Greymouth on SH73 and SH6. Arnold and Grey valleys- Jacksons to Greymouth on Midland Railway line and SH7. | 27/02/1918 to 19/02/2003 | Transit NZ Ltd. Ministry of Works. Grey District Council. Transfield Ltd. Tranzrail Ltd. WCRC natural Hazards Review | Study area limited to the transportation corridors from Arthur's Pass to Greymouth. |

| Study/source | Geographic area | Dates | Sub-sources | Comments |
|---|---|---|---|---|
| Cooper, 2000. | Buller District. | 1999 | Buller District Council | No information on dates of failure, so simply shows a “snapshot” of observable landslides during the study period. Also, limited to personal observations by the author. |
| GNS landslide catalogue. | Nationwide, so covers the entirety of this study area. | 12/08/1997 to 12/01/2009 | National and local newspapers. Hazardwatch. National Radio. Original research | Limited to slides >1km$^2$. Not focused on infrastructure. |

| Study/source | Geographic area | Dates | Sub-sources | Comments |
|---|---|---|---|---|
| WCRC landslide archive. | West Coast Region | 13/01/1945 to 29/07/2009 | Benn, 1990.<br>Benn, 1992.<br>Patterson and Berrell, 1995.<br>Greymouth Evening Star.<br>Westport News.<br>Lowe, 2001.<br>Fulton, 2004.<br>Power and Anderson, 1992.<br>The Press.<br>Patterson and Bourne-Webb, 1994<br>Johnston, 1971<br>Buller District Council.<br>Westland District Council.<br>Grey District Council.<br>Personal observations by WCRC Natural Hazards Analyst, M. Trayes. | Sporadic entries-some years missing.<br>Essentially based on Benn's (1990) inventory, which was derived from a flood hazard study.<br>Newspaper archives formed the bulk of Benn's (1990) study, which did not include the Westport News archives.<br>Only recent entries from Westport News are included. |
| OPUS Consultants | West Coast Region, State Highway network | 08/01/2004 to 17/11/2009 | Roading Contractors | Data limited to date, location and volume of material transported away from the site. No description of trigger or actual movement characteristics. |

| Study/source | Geographic area | Dates | Sub-sources | Comments |
|---|---|---|---|---|
| OnTrack | West Coast Region, Railway Network: Midland line, Stillwater-Westport line, Rapahoe line, Hokitika Industrial line. | 01/01/2005 to 11/01/2010 | Locomotive Engineers, maintenance staff. | Results of a search of the OnTrack Incident Reporting System (IRIS) with landslide, slip and subsidence as keywords. |

Further additions to this catalogue were made by searching the archives of the Westport News at the Westport News offices in Westport and searching the archives of the Grey Star and the Hokitika Guardian at the Grey Star offices in Greymouth. Personally-observed landslides were included wherever possible.

Each catalogue entry is identified by a unique identification number (ID number) and the following fields have been populated to give as complete a record of the landslide events as possible:

- Date. Essential for calculating magnitude/frequency relationships and temporal distribution patterns.
- Location. A descriptive term is included and the corresponding Easting and Northing was recorded to allow display in GIS. Where coordinate pairs were not recorded a search of the descriptive names of landslide locations on standard topographic maps, internet searches and local knowledge was used to assign coordinate pairs where possible. For entries concerning road and railway records the calculation of coordinates from Exact Road Positions (ERP) locations or Railway Miles locations was possible using the Calibrate Routes tool in ArcGIS toolbox.
- Description. A brief description of the landslide was included where the observer had recorded this. Unfortunately, this field is blank in many cases as the observer simply records the date, damage and location.
- Type. Slope movement classification was included where the description was adequate. In the interests of uniformity of terminology between studies, the classification system of Cruden and Varnes' (1998) was used and the abbreviations used in the catalogue are as follows:

  Rock fall (RF), Debris fall (DF), Earth fall (EF), Rock topple (RT), Debris topple (DT), Earth topple (ET), Rock slide (RS), Debris slide

(DS), Earth slide (ES), Rock flow (RFL), Debris flow (DFL), Earth flow (EFL)

- Trigger information is recorded where possible and has been divided into rainfall-generated (R), earthquake-generated (EQ), erosion by river or coastal action (E), anthropogenically-generated (A) and unknown (U).
- 24 hour rainfall amount was recorded for rainfall generated landslides. Rainfall records were obtained from the “Hilltop” meteorological database held and maintained by the WCRC. This database holds rainfall records from a network of gauges maintained and operated by the MetService, NIWA, WCRC and BDC. Records from two gauge stations owned and maintained by Solid Energy at Stockton were also used. Figures for the preceding 24hr period are presented. Database entries are generally by date only, with no time information, so a period of 12 noon on the preceding day to 12noon on the day of the landslide was used as the 24 hour rainfall figure. The gauge station closest to the landslide event was used regardless of prevailing wind and incident weather direction. Table 3.6 shows the rainfall data available and the data provider.
- EQ magnitude was recorded for earthquake-generated landslides.
- Volume of slip material was estimated in cubic meters and recorded where possible.
- Additional comments were also recorded.
- Deaths. Where a landslide has resulted in death this has been recorded.
- Data source and sub-source has also been recorded. For example, if a record of a landslide was found in the Greymouth Evening Star and included in Smith’s (2004) inventory it will be recorded as Greymouth Evening Star in “Source” and Emily Smith as the “Sub-source”.

**Table 3.6.** Rainfall gauge locations, dates of data collection and the data providing authority.

| Gauge name | Dates | Data provider |
|---|---|---|
| Ahaura River at gorge | 1987-present | WCRC |
| Arnold River at Inchbonnie | 1949-1999 | Met Service |
| Arnold River at Moana | 1989-present | NIWA |
| Arnold River at Rotomanu | 1967-2004 | Met Service |
| Buller River at Harbourmaster's Office | 2002-present | Buller District Council |
| Butcher's Creek at Butcher's Gully, Kaniere | 1972- present | NIWA |
| Crooked River at Kaimata Range | 1987-1992 | WCRC |
| Cropp River at hut | 1979-present | NIWA |
| Granity | 2007-present | Solid Energy |
| Grey River at Conical Hill | 1987- present | WCRC |
| Greymouth Airport | 1947-2004 | Met Service |
| Haast River at Roaring Billy | 1989-present | NIWA |
| Hokitika River at Prices Flat | 1971-2006 | NIWA |
| Inanguhua River at Landing | 1993-present | WCRC |
| Karamea River at Arapito | 1978-2005 | NIWA |
| Karamea River at Gorge | 2001-present | WCRC/NIWA |
| Mt. Frederick | 1999-present | Solid Energy |
| Sirdar Creek at Paparoa | 1986-present | WCRC |
| Styx River | 1989-present | WCRC |
| Taramakau River at Otira | 1906-1987 | Met Service |
| Waiho at SH 6 bridge | 2002-2006 | WCRC/NIWA |
| WCRC office at Paroa | 2004-present | WCRC |
| Whataroa | 1985-2007 | NIWA |

The resultant landslide catalogue is by far the most complete record of damaging landslides in the region so far compiled. It can be used to illustrate the history and character of landslides for a selected area, or to give regional trends of landslide types, rainfall trigger levels, etc.

# Chapter 4. Methodology used for landslide susceptibility modelling

## 4.1 Introduction

A landslide susceptibility map indicates areas likely to have landslides in the future by correlating some of the principal factors that contribute to landslides with the past distribution of landslides (Yalcin, 2008). It relies on the trusted geological principle that "the past and the present are the keys to the future". That is, future landslides are most likely to occur under the same conditions that led to past and present landslides (Dai and Lee, 2002). The most commonly used methods in landslide susceptibility assessments are geomorphological hazard mapping, analysis of landslide inventories, heuristic or index-based methods, geotechnical or physically-based models and statistical models (Huabin *et al.,* 2005). Statistical modelling removes the subjectivity of expert-opinion-based assessments, but the reliability of the resultant maps depends on the amount and quality of available data, the working scale and the selection of the appropriate methodology of analysis and modelling (Yalcin, 2008).

During early experimentation (in this study) with this technique it became obvious that the terrain variables that act as control factors in the occurrence of landsides are very different across the study area. One of the criticisms of this type of modelling is that a high degree of simplification is required (Fell *et al.,* 2008; Dai and Lee, 2002) especially in large study areas such as the West Coast region. The geologic, tectonic, geomorphic and environmental conditions in the coastal plains are very different than those present in the Southern Alps. Correspondingly, the environmental controls on landsliding are also different and the distributions of landslide occurrences reflect this. For this reason it was decided that the study area be divided into two distinct areas as shown in figure 4.1.

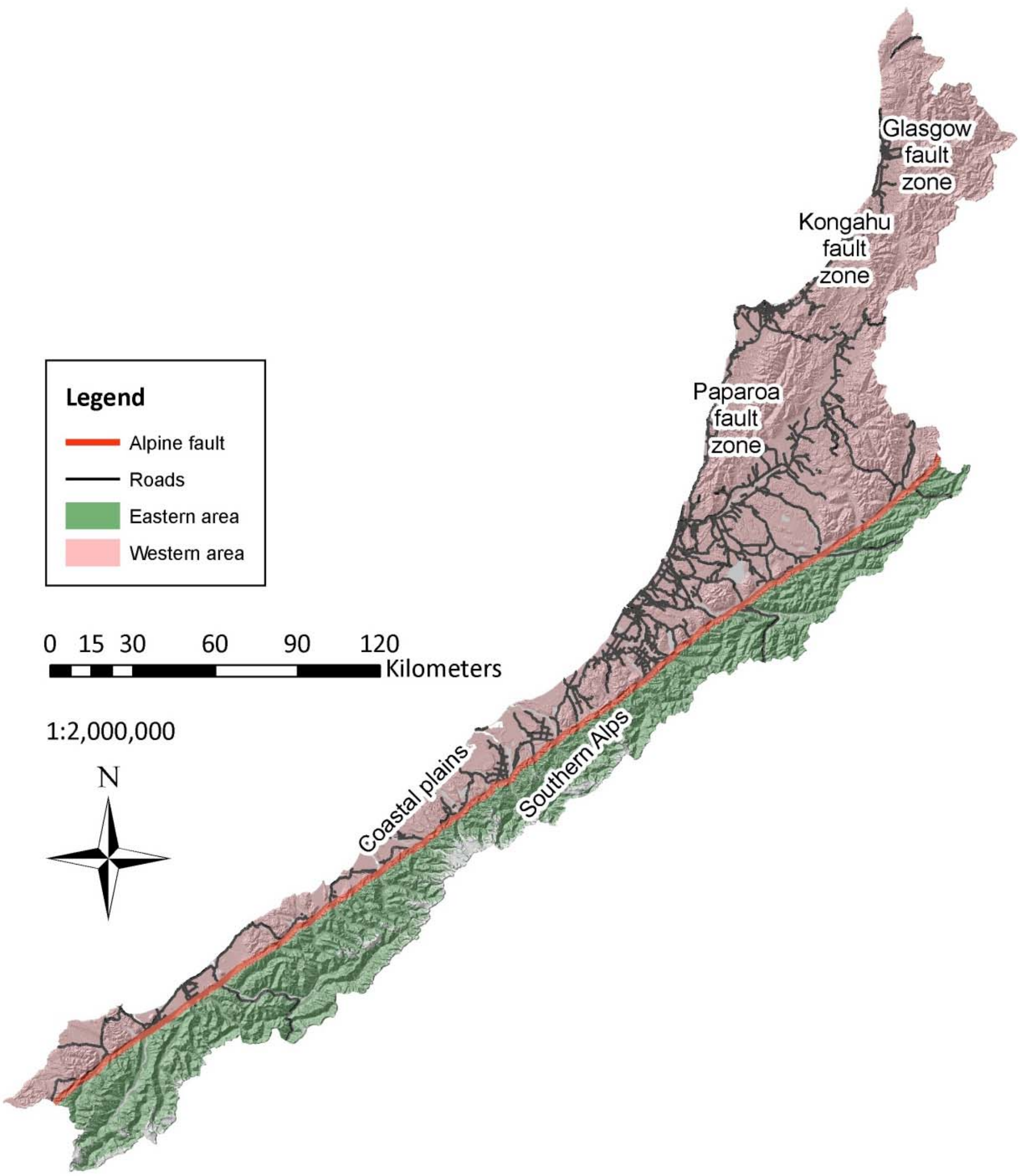



**Figure 4.1.** Locations of the two distinct study areas.

The Alpine fault is the largest tectonic feature in the West Coast region, and conveniently separates the region into:

1. East of the Alpine fault. This area encompasses the Southern Alps, from the Alpine fault to the Main Divide. Geologically, it is dominated by schist with decreasing metamorphic grade to the east, and an obvious mylonite zone in close proximity to the Alpine fault. It generally has high mountains and steep westward-draining valleys, with varying depths of alluvial and landslide-derived debris on the valley floor. Very heavy orographic rainfall is common

in the Southern Alps with many areas receiving over 10m of annual rainfall, and 24 hour rainfall of over 200mm is not uncommon.

2. West of the Alpine fault. This area encompasses the coastal plains and a varied stratigraphy with a granite and greywacke basement. This is unconformably overlain by a thick sedimentary succession of coastal marine and fluvial sediments including coal measures, limestone and shale. The mountains in the north of the region are generally lower and less steep than the Southern Alps. However, regional faulting along the Paparoa, Kongahu and Glasgow fault zones has created uplift and associated denudation in the Western side of the region. Rainfall is generally not as heavy as in the Southern Alps.

For these reasons, the modelling of landslide behaviour and distribution was handled separately in these two areas.

Figure 4.2 illustrates the process of making a landslide susceptibility map. Thematic factor maps representing the factors assumed to be important in the control of landslide occurrence are prepared in a GIS and after grouping the classes into sensible sets the maps can be rasterized in preparation for overlay analysis. Each factor map is overlayed with the landslide inventory and the density of landslides in each class is then calculated. Following this, a weight is applied to each class within each factor map and the resultant maps can then be overlayed, following defined rules, to produce a landslide susceptibility index (LSI) map. This map can then be divided into zones representing low to high susceptibility to landsliding, based on a validation performed using a landslide distribution derived from new aerial photography.

As can be seen in this diagram the weights of evidence method was used to generate a set of LSI maps and the analytical hierarchy process was used to create another set of LSI maps. The results of these were then tested and compared in order to find the most appropriate technique.

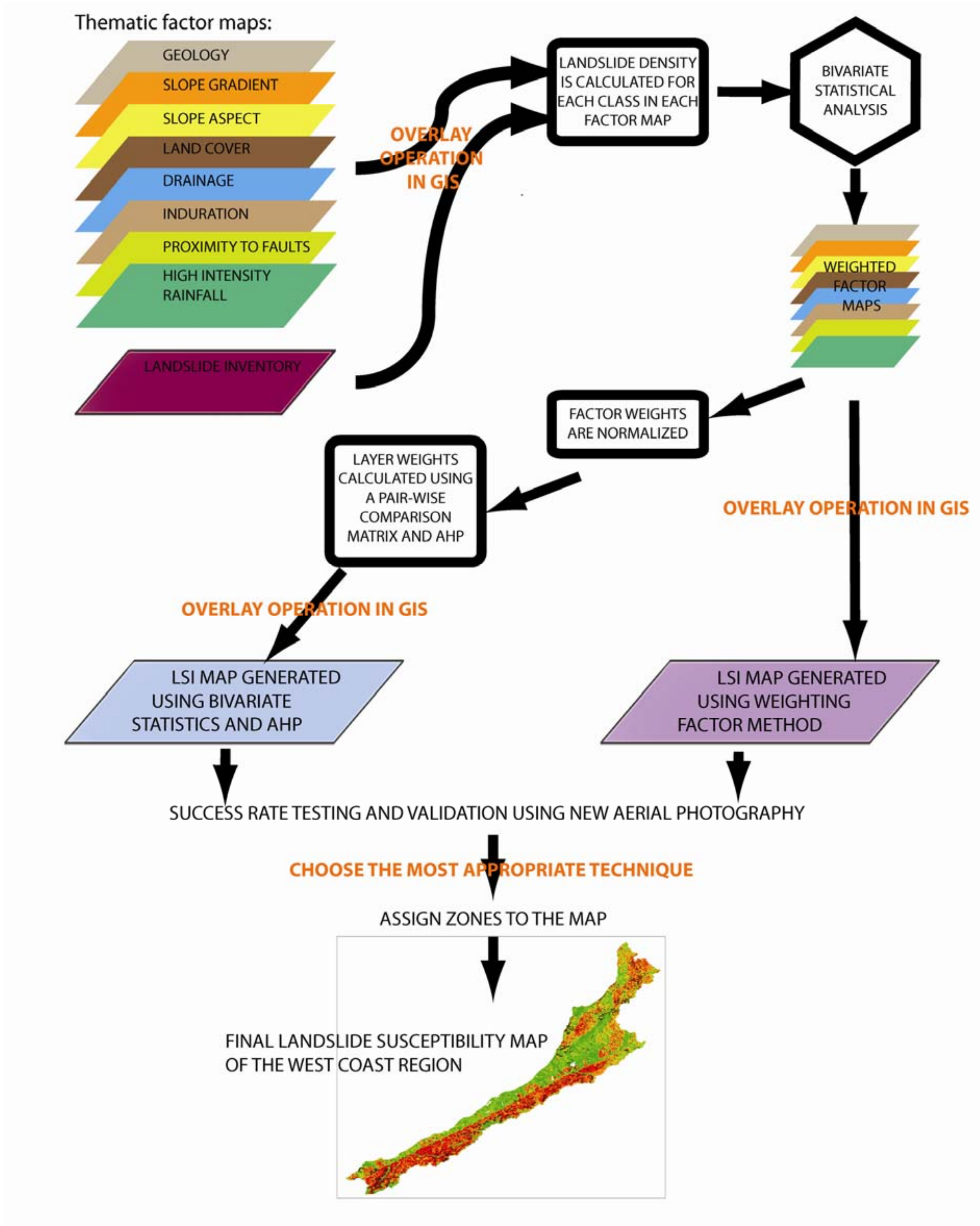



**Figure 4.2.** Flow diagram representing the steps used in this study to produce a landslide susceptibility map for the West Coast region.

The weights of evidence method was first developed by Bonham-Carter (1994) for use in mineral potential assessment for the mining industry. It has also been used successfully to locate flowing oil wells, spatially define the relationship between faults and seismicity, and map cliff instabilities associated with mine subsidence (Dahal *et al.*, 2008). Since Van Westen *et al.* (2003) applied it to landslide susceptibility analysis, it has been successfully used for this purpose in many different and diverse study areas (Dai and Lee, 2002; Gullà *et al., 2008;* Neuhäuser and Terhorst, 2007; Nandi and Shakoor, 2009; Thiery *et al.,* 2007; Cevic and Topal, 2003, Suzen and Doyuran, 2004) producing landslide susceptibility maps that have been used for planning natural gas pipeline routes, land-use planning and civil defence emergency planning.

In a bivariate statistical analysis, each factor's influence on landsliding is considered separately and the assumption is made that the factors are conditionally independent of each other (Dahal *et al.,* 2008). The assumption of conditional independence has been criticized as an oversimplification (Yalcin, 2008; Magliulo *et al.,* 2009). To address this, the results obtained by the weights of evidence method have been further refined, by applying the analytical hierarch process, or "AHP" (Saaty, 1978) to the modelled outputs. AHP is a flexible, yet structured decision tool that can be used for solving complex problems by structuring them into a hierarchical framework (Boroushaki and Malczewski, 2008). It has been used for many purposes including bankruptcy prediction (Park and Han, 2002), medical and health care decisions (Liberatore and Nydick, 2008), biodiversity representation (Moffett *et al.,* 2006), evaluation of biofuels (Papalexandrou *et al.,* 2008), selection of mining methods (Naghadehi *et al.,* 2009) as well as various landslide predictive models (Dai *et al.,* 2001; Komac, 2004; Yalcin, 2008; Liu and Chen, 2003).

The AHP procedure involves 3 major steps: (i) establishing the hierarchy, (ii) pairwise comparison of elements of the hierarchical structure, and (iii) constructing an overall priority rating. In the present work it is used to assign relative weights to each factor map, ie. deciding which factors play greater and lesser roles in the control of landslides.

The weights of evidence method assigns weights to the different classes within each factor map, but is limited by the assumption that the factors are conditionally independent of each other. In recognition of the fact that interdependencies exist between the various landslide conditioning factors the AHP has been used to assign weights to the factor maps. In this way, the effect of subjectivity of the researcher is minimized, yet the problem of assuming conditional independence between the landslide conditioning factors is addressed.

The output of this is a series of landslide susceptibility index (LSI) maps, which display a continuum of values, representing very low to very high susceptibility to landsliding. Since the area to the east of the Alpine fault has been handled separately from the area to the west of the Alpine fault this has produced four LSI maps:

1. LSI map of the Eastern area generated using the weighting factor method only.
2. LSI map of the Western area generated using the weighting factor method only.
3. LSI map of the Eastern area generated using the AHP method.
4. LSI map of the Western area generated using the AHP method.

Evaluating the performance of a landslide susceptibility map is necessary to ensure the reliable application to landslide hazard management (Frattini *et al.,* 2010). The evaluation was completed using the success rate testing method of Chung and Fabbri (1999). These maps were then validated using a new set of aerial photographs obtained from the Animal Health Board. This allows quantitative comparisons of the success rates and predictive power of the resultant maps. The maps with the best predictive capabilities can then be chosen to use as a landslide hazard management tool.

Assigning zones to the validated LSI maps is the last stage in producing landslide susceptibility maps. This is achieved by placing the boundaries between the 5 zones (very low, low, moderate, high and very high) at LSI values which will place certain proportions of the landslide distribution in each zone. For example the boundary between high and very high susceptibility can be set such that 70% of the mapped landslides fall in the very high susceptibility zone. This applies a quantitative aspect to an otherwise qualitative term for the susceptibility zones (Fell *et al.,* 2008).

It is important to note that the resultant map is a representation of where landslide occurrences are more or less likely to occur. It does not attempt to define the velocity, volume or run-out distances of these landslides. To define the velocity, volume and run-out distance of a landslide it is necessary to conduct detailed analysis of parameters such as slope geometry, rheology, soil cohesion, etc, so is not possible at the regional scale. However, the prediction of run-out characteristics may be necessary to define the actual landslide hazard in site-specific studies at a later stage.

## 4.2 Methodology

### 4.2.1 Bivariate statistics

Weights of evidence modelling is a bivariate statistical technique that uses the Bayesian probability model and calculates a weight for each landslide causative factor based on the presence or absence of landslides in the area. In bivariate statistical analysis, each factor's influence on landsliding is considered separately and the assumption is made that the factors are conditionally independent of each other (Dahal *et al.,* 2008). Positive and negative weights ($W_i^+$ and $W_i^-$) are assigned to each of the classes into which a factor map is divided (e.g. land use classes within a land use map, or lithological units in a geology map) and are defined as follows:

$$W_i^+ = \log e \frac{P\{B_i|S\}}{P\{B_i|\bar{S}\}} \qquad (1)$$

and

$$W_i^- = \log e \frac{P\{\bar{B}_i|S\}}{P\{\bar{B}_i|\bar{S}\}} \qquad (2)$$

Where $P$ is the probability, $B_i$ = presence of the potential landslide conditioning factor, $\bar{B}_i$ = absence of a potential landslide conditioning factor, $S$ = presence of a landslide, and $\bar{S}$ = absence of a landslide (Van Westen *et al.,* 2003).

Each factor map is displayed in a raster format which depicts the classes in 25m x 25m pixels. When a factor map is overlayed with the landslide inventory map the numbers of pixels can be counted as described in table 4.1.

**Table 4.1.** The four possible combinations of pixels from an overlay of a landslide inventory map and a landslide conditioning factor map.

| | | $B_i$ : Potential landslide conditioning factor | |
|---|---|---|---|
| | | Present | Absent |
| *S:* Landslide occurrence | Present | $Npix_1$ | $Npix_2$ |
| | Absent | $Npix_3$ | $Npix_4$ |

Based on equations (1) and (2) the weights of evidence can be written in terms of number of pixels as follows.

$$W_i^+ = \log_e \frac{\frac{Npix_1}{Npix_1+Npix_2}}{\frac{Npix_3}{Npix_3+Npix_4}} \quad (3)$$

and

$$W_i^- = \log_e \frac{\frac{Npix_2}{Npix_1+Npix_2}}{\frac{Npix_4}{Npix_3+Npix_4}} \quad (4)$$

For each factor, $W_i^+$ is used for the pixels that represent a factor whose presence is favourable for the occurrence of landsides, and $W_i^-$ is used for the pixels that represent a factor whose absence is favourable for the occurrence of landslides. So, if $W_i^+$ is positive the presence of the factor is favourable for the occurrence of landslides and if it is negative, the presence of that factor is not favourable for the occurrence of landslides. Also, if $W_i^-$ is positive the absence of the factor is favourable for the occurrence of landslides (Van Westen *et al.,* 2008).

Since the factor maps represent different classes, the presence of one class implies the absence of the other classes in the same map. Therefore, to obtain the total weight ($W_i$) for each factor class, the positive weight for the class was added to the negative weights of the other classes in the same map.

Bivariate statistical techniques utilise the assumption that the different factor maps are conditionally independent of each other, therefore the actual relationships between the factors are not explored or analysed. The original technique proposed by Bonham-Carter (1994), and later used by Van Westen (2002) and others (e.g.

Cevik and Topal, 2003; Dahal *et al.*, 2008; Neuhauser and Terhorst, 2007; Thiery *et al.,* 2007) for landslide susceptibility modelling applies equal weights to each layer. The assumption here is that if a factor map contains classes with weights that have extreme values it is useful for susceptibility mapping, while factors with weights around zero have no relation with the occurrence of landslides (Van Westen, *et al.,* 2003).

All thematic factor maps are stored in raster format and the resulting total weights are applied to the respective classes on each thematic map. Using an overlay function in a GIS the weights between the layers can be summed producing a landslide susceptibility index (LSI) map, which reflects the weights on all factor maps.

### 4.2.2 Analytical hierarchy process

It has been recognised that the assumption that the different factor maps are conditionally independent of each other is an oversimplification of a complex problem (Magliulo *et al.,* 2009). In this study, the original weighting factor method has been followed and tested, but in addition to this, the analytical hierarchy process (AHP) of Saaty (1978) has been used to address the issue of what weights to apply to each layer.

The AHP works on the premise that decision-making of complex problems can be simplified by structuring it into a simple hierarchical structure. The AHP can be summarized into three main steps:

1. Structuring of a problem into a hierarchy consisting of a goal and subordinate features.

2. Establishing pair-wise comparisons between elements (criterion) at each level.

3. Synthesis and establishing the overall priority to rank the alternatives.

In the case of landslide susceptibility modelling, the “goal” is the calculation of a landslide susceptibility value for any discrete point on a map. The subordinate features are the various factor maps: aspect, drainage, geology, slope, etc. and the various classes within these maps. Once the hierarchical structure is established, a pair-wise comparison is carried out between any two criteria. The levels of the pair-wise comparisons range from 1 to 9, where ‘‘1’’ represents that two criteria are equally important, while the other extreme ‘‘9’’ represents that one criterion is absolutely more important than the other. Table 4.2 defines and explains these levels as proposed by Saaty (1978). Solution of the AHP hierarchical structure is obtained by synthesizing all the preference weights to obtain the overall priority weight (Saaty 1978).

**Table 4.2.** Scale of relative importance suggested by Saaty (1978).

| Intensity of importance | Definition | Explanation |
|---|---|---|
| 1 | Equal importance | Two activities contribute equally to objective |
| 3 | Weak importance of one over another | Experience and judgment slightly favour one activity over another |
| 5 | Essential or strong importance | Experience and judgment strongly favour one activity over another |
| 7 | Demonstrated importance | An activity is strongly favoured and its dominance demonstrated in practice |
| 9 | Absolute importance | The evidence favouring one activity over another is the highest possible order of affirmation |
| 2, 4, 6, 8 | Intermediate values between the two adjacent judgments | When compromise is needed |
| Reciprocal of above numbers | If an activity *i* has one of the above numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*. | |

These overall priority weights, or Eigen vectors, are calculated from the pair-wise comparison matrix in the following manner (modified from Saaty and Vargas, 1991):

1. Consider 3 options; *a, b and c.* A pair-wise comparison matrix is produced using the scale of relative importance as described in table 2. Note the reciprocal value is used for negative preference.

| | *a* | *b* | *c* |
|---|---|---|---|
| *a* | 1 | 1/3 | 5 |
| *b* | 3 | 1 | 7 |
| *c* | 1/5 | 1/7 | 1 |

2. Each column of the matrix is summed.

| | *a* | *b* | *c* |
|---|---|---|---|
| *a* | 1 | 1/3 | 5 |
| *b* | 3 | 1 | 7 |
| *c* | 1/5 | 1/7 | 1 |
| Sum | 21/5 | 31/21 | 13 |

3. Each element of the matrix is divided by the sum of its column, thus normalizing the matrix elements. The sum of each column is 1.

| | *a* | *b* | *c* |
|---|---|---|---|
| *a* | 5/21 | 7/31 | 5/13 |
| *b* | 15/21 | 21/31 | 7/13 |
| *c* | 1/21 | 3/31 | 1/13 |
| Sum | 1 | 1 | 1 |

4. The normalized priority weight is then calculated for each option by averaging across the rows.

| | *a* | *b* | *c* | Priority weight |
|---|---|---|---|---|
| *a* | 5/21 | 7/31 | 5/13 | 0.2828 |
| *b* | 15/21 | 21/31 | 7/13 | 0.6434 |
| *c* | 1/21 | 3/31 | 1/13 | 0.0738 |

The priority weight, or Eigen vector, is used in this study as the factor map weight. The AHP can be used to establish the weights to apply to each class within a factor map, but since this has already been achieved with the weighting factor method, it has been used here only to establish the relative importance of one factor map compared to another.

Since the AHP applies weights to the factor maps, the weights for each class are normalised before further processing. Then, using the same overlay function as in the weighting factor method, a weighted sum procedure, within a GIS, delivers the output LSI map.

### 4.2.3 Success rate testing

LSI maps generated with these two processes were tested for their success rates (Chung and Fabbri, 2003) by comparing the distribution of landslides in the landslide inventory layer to the LSI values. This technique has been used by many authors as a validation technique (Sarkar *et al.*, 2008; Dahal *et al.*, 2008; Cevik and Topal, 2003; Yalcin, 2008). However, this has come under criticism from others (Van Westen *et al.,* 2003; Magliulo *et al.,* 2009; Suzen and Doyuran, 2004; Huabin *et al.,* 2005; Remondo *et al.,* 2003), as it merely shows how good the resulting LSI values can explain the input landslide pattern that was used to calculate them.

Nevertheless, it is a useful tool to show the “goodness of fit” of the statistical classification used to produce the LSI map and is performed as follows: The success rate is calculated by ordering the pixels of the LSI maps and grouping into 100 classes from high to low values, in a quantile distribution based on the frequency information from the histogram of their distribution. After that, the landslide inventory is overlayed with the categorised LSI map and the joint frequency is then plotted on a scatter graph (Chung and Fabbri, 2003; Van Westen *et al.,* 2003). The resulting curve shows the percentage of the susceptibility map that is required to predict a certain percentage of landslides. The further up and away from a true diagonal, the better the accuracy of the map.

#### 4.2.4 Validation

To perform an actual validation, which will test the predictive power of the susceptibility maps, a new set of aerial photography that was not used in the original bivariate statistical analysis is required (Van Westen *et al,.* 2003; Fell *et al.,* 2008). By comparing the distribution of landslides mapped from the validation aerial photography to the LSI maps a true assessment of their predictive power can be made. A success rate curve is generated in the same manner as the success rate testing, but since this landslide distribution was not used to generate the LSI map it is a true test of its predictive power.

The LSI maps were validated by cross referencing with an inventory of 634 landslides mapped from an aerial photograph dataset obtained from the Animal Health Board. These aerial photographs were not used in the initial landslide inventory mapping, so can be used to test the predictive power of the susceptibility maps. Figure 4.3 shows the locations of the available aerial photography used for the validation.

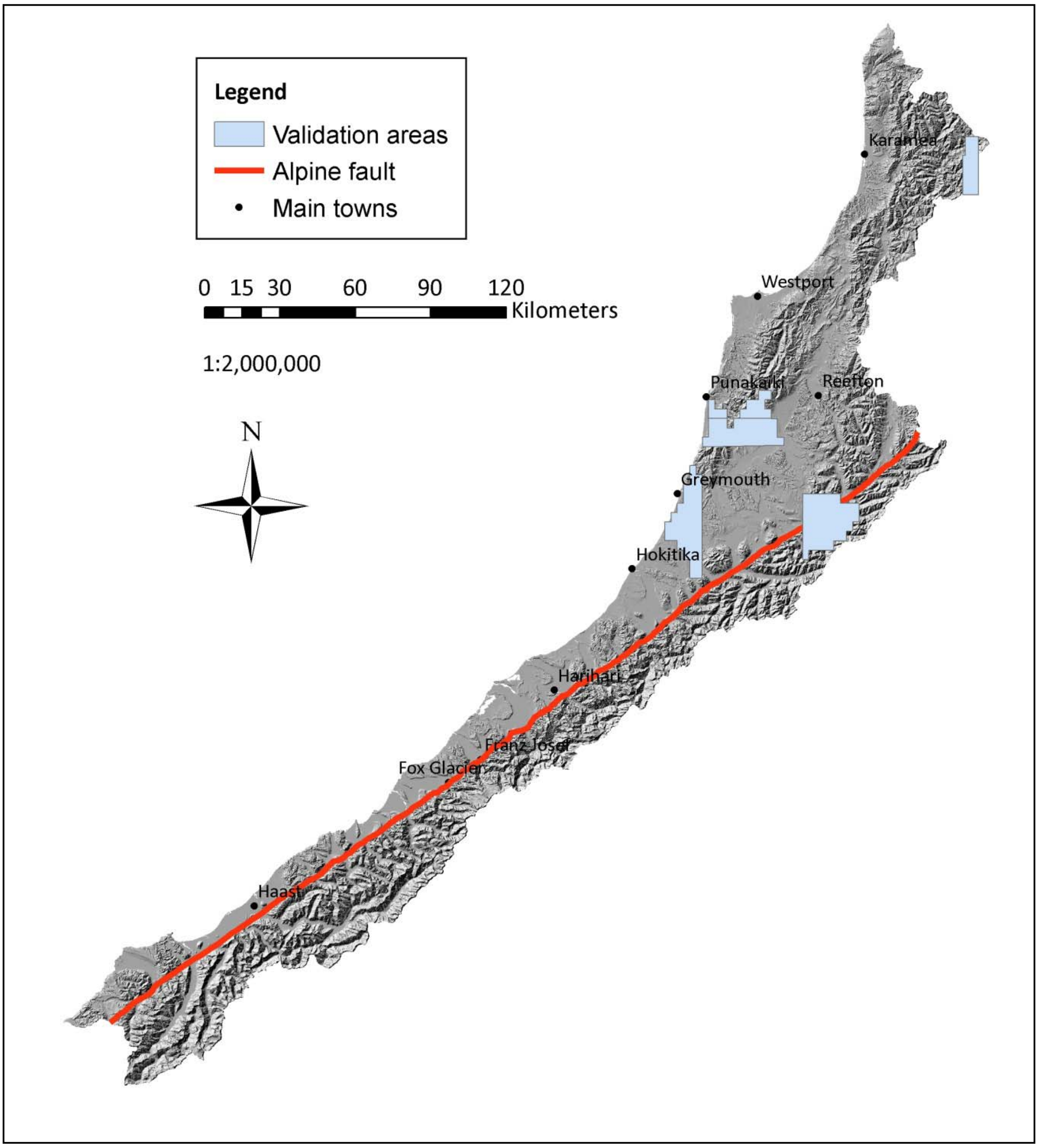



**Figure 4.3.** Aerial photography areas used for the validation.

### 4.2.5 Assigning zones to the landslide susceptibility map

For the purposes of validating the maps the susceptibility scores were reclassified in a scale of 1-100. This is useful for interrogating the predictive power of the maps. However, the usefulness of a susceptibility map is greatly increased when it is divided into 5 zones: very low, low, moderate, high and very high susceptibility to landsliding (Fell *et al.*, 2008). This zoning is accomplished by assigning LSI values to the boundaries between the zones such that a certain proportion of the mapped landslides fall within each zone. This gives a quantitative value to the susceptibility map zones and is therefore useful in providing the end user with relative landslide probabilities. Once the zones are established, further interrogation of the map is possible and values relating to landslide density and total landslide counts for each zone can be presented thus enhancing the quantitative aspects of the map.

Figure 4.4 illustrates the difference between an LSI map, showing a continuous variable (LSI) map and a susceptibility map, which has 5 distinct zones.

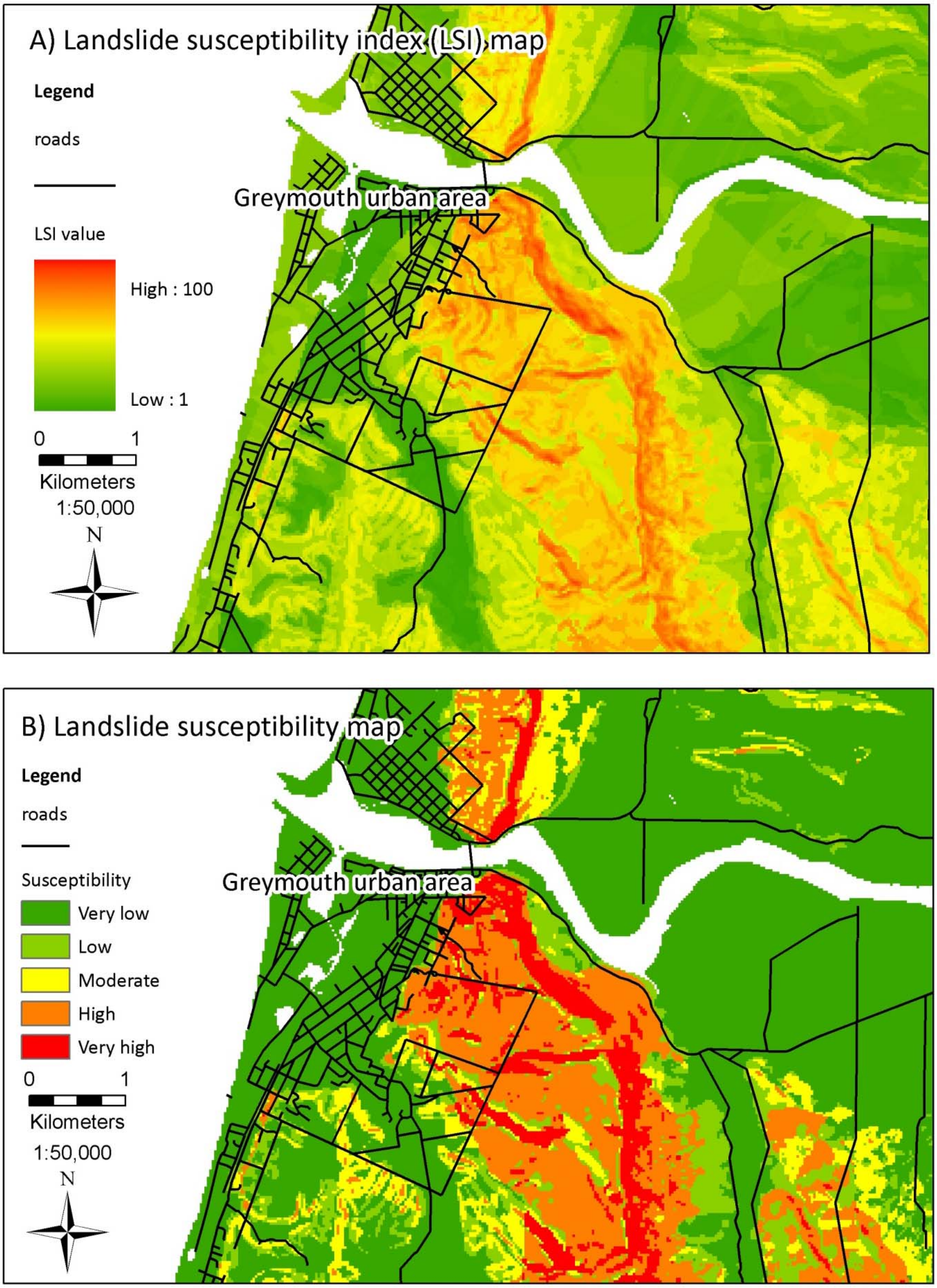



**Figure 4.4.** A comparison of an LSI map (A) and a landslide susceptibility map (B) with 5 susceptibility zones.

The usefulness of a zoned susceptibility map is far greater than an LSI map, as rules relating to land use and development planning can be attached to each of the zones and the boundaries are easily visible. Also, the spatial characteristics of the zones can be quantitatively explored giving more meaning to the classification of the zones.

## 4.3 Summary

The chosen methodology is a robust technique that satisfies the proposed framework suggested in “Guidelines for landslide susceptibility, hazard and risk zoning for land use planning”, which was published in 2008 by the Joint Technical Committee on Landslides and Engineered Slopes (Fell *et al.,* 2008). The weights of evidence modelling technique of Bonham-Carter (1994), has been successfully used by many landslide researchers (eg. Van Westen, 2003; Dai and Lee, 2002; Gullà *et al., 2008;* Neuhäuser and Terhorst, 2007; Nandi and Shakoor, 2009; Thiery *et al.,* 2007; Cevic and Topal, 2003, Suzen and Doyuran, 2004) and the AHP developed by Saaty (1978) has been widely used to refine these results (Dai *et al.,* 2001; Komac, 2004; Yalcin, 2008; Liu and Chen, 2003).

The success rate testing and validation process is used to choose the most accurate resulting maps and adds credibility to the results. It also promotes effective use of the finished landslide susceptibility maps by defining the accuracy, uncertainty and therefore the limitations of the final maps.

Finally, the technique used to assign the zones to the map, produces an easily readable map which can then be used effectively for landslide hazard management purposes.

# Chapter 5. Results of the landslide susceptibility modelling

## 5.1 Introduction

This chapter presents the results of the landslide susceptibility modelling. The landslide susceptibility maps derived from the two techniques (weighting factor method and analytical hierarchy process) are tested and validated using a new landslide inventory derived from a new set of aerial photographs. The map with the higher success rate is then chosen and five zones are then applied based on the landslide density. A brief presentation of the characteristics of these zones is included. The actual landslide susceptibility map is available in appendix A.

## 5.2 Calculation of total weights using bivariate statistics

Following the procedure described in chapter 4, total weights ($W_i$) for all classes in each factor map were calculated. The resulting total weights indicate the importance of each factor class in the control of landsliding. If the total weight is positive, it is favourable for the occurrence of landslides; if it is negative, it is not (van Westen *et al.,* 2003). The frequency ratio (%landslide area/%class area) is useful to assist in assessing the relationship between the controlling factors and landslide occurrences (Dahal *et al.*, 2008)

**Table 5.1** Calculated total weights ($W_i$) for all classes in all factor maps.

| Aspect | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Class# | Description | Total area/ pixels | | Landslide area/ pixels | | Frequency ratio (%) | | Total weight ($W_i$) | |
| | | **East** | **West** | **East** | **West** | **East** | **West** | **East** | **West** |
| 1 | Flat | 4030 | 26806 | 15 | 154 | 0.37 | 0.57 | 0.11 | 0.15 |
| 2 | North | 2048578 | 3188025 | 6926 | 10703 | 0.34 | 0.34 | 0.27 | 0.25 |
| 3 | Northeast | 1422362 | 2745580 | 5028 | 9670 | 0.35 | 0.35 | 0.30 | 0.30 |
| 4 | East | 1244455 | 2339549 | 4476 | 8068 | 0.36 | 0.34 | 0.31 | 0.27 |
| 5 | Southeast | 1308211 | 2150641 | 3615 | 6294 | 0.28 | 0.29 | 0.02 | 0.08 |
| 6 | South | 1463481 | 2287907 | 2863 | 4724 | 0.20 | 0.21 | -0.37 | -0.31 |
| 7 | Southwest | 1447603 | 2937536 | 2512 | 4936 | 0.17 | 0.17 | -0.50 | -0.54 |
| 8 | West | 1803816 | 3460479 | 3751 | 6797 | 0.21 | 0.20 | -0.31 | -0.38 |
| 9 | Northwest | 2064236 | 3591348 | 5522 | 10423 | 0.27 | 0.29 | -0.02 | 0.08 |

| Slope gradient | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Class# | Description | Total area/ pixels | | Landslide area/ pixels | | Frequency ratio (%) | | Total weight($W_i$) | | |
| | | **East** | **West** | **East** | **West** | **East** | **West** | **East** | **West** |
| 1 | 0-10˚ | 981143 | 9080644 | 1424 | 4553 | 0.15 | 0.05 | -0.67 | -2.05 |
| 2 | 10-20˚ | 1433143 | 3969429 | 2602 | 8421 | 0.18 | 0.21 | -0.45 | -0.22 |
| 3 | 20-25˚ | 1243378 | 2145582 | 2204 | 6078 | 0.18 | 0.28 | -0.47 | 0.12 |
| 4 | 25-30˚ | 1718520 | 2221806 | 3831 | 8082 | 0.22 | 0.36 | -0.23 | 0.41 |
| 5 | 30-35˚ | 2092007 | 2154966 | 5807 | 10200 | 0.28 | 0.47 | 0.02 | 0.71 |
| 6 | 35-40˚ | 2090528 | 1713234 | 7111 | 10516 | 0.34 | 0.61 | 0.27 | 1.00 |
| 7 | 40-45˚ | 1548148 | 948130 | 5615 | 7845 | 0.36 | 0.83 | 0.33 | 1.29 |
| 8 | 45-50˚ | 897647 | 358883 | 3245 | 4012 | 0.36 | 1.12 | 0.31 | 1.55 |
| 9 | 50˚+ | 802258 | 135197 | 2869 | 2062 | 0.36 | 1.53 | 0.29 | 1.84 |

| Geology | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Class# | Description | Total area/ pixels | | Landslide area/ pixels | | Frequency ratio (%) | | Total weight ($W_i$) | |
| | | **East** | **West** | **East** | **West** | **East** | **West** | **East** | **West** |
| 1 | Quaternary unconsolidated sediments | 1939844 | 9490591 | 4070 | 8537 | 0.21 | 0.09 | -0.21 | -1.46 |
| 2 | Coarse grained sediments | 46612 | 627507 | 75 | 1700 | 0.16 | 0.27 | -0.43 | 0.03 |
| 3 | Fine grained sediments | 17443 | 1420591 | 15 | 8077 | 0.09 | 0.57 | -1.06 | 0.85 |
| 4 | Granitoids | 548 | 4969523 | 1 | 22859 | 0.18 | 0.46 | -0.31 | 0.78 |
| 5 | Mafics and ultramafics | 107698 | 17724 | 331 | 31 | 0.31 | 0.17 | 0.22 | -0.41 |
| 6 | Medium grained sediments | 1554585 | 3547797 | 5403 | 10481 | 0.35 | 0.30 | 0.38 | 0.13 |
| 7 | Low to medium grade metamorphics | 8778310 | 588944 | 22223 | 1973 | 0.25 | 0.34 | -0.11 | 0.25 |
| 8 | High grade metamorphics | 323738 | 1045400 | 2476 | 2937 | 0.76 | 0.28 | 1.18 | 0.07 |
| 9 | Limestone | N/A | 717763 | N/A | 4974 | N/A | 0.69 | N/A | 1.03 |
| 10 | Peat | 37952 | 301622 | 115 | 196 | 0.30 | 0.06 | 0.20 | -1.41 |

| Drainage | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Class# | Description | Total area/ pixels | | Landslide area/ pixels | | Frequency ratio (%) | | Total weight ($W_i$) | |
| | | **East** | **West** | **East** | **West** | **East** | **West** | **East** | **West** |
| 1 | Very poor | 353822 | 625800 | 241 | 166 | 0.07 | 0.03 | -1.47 | -3.11 |
| 2 | Poor | 29916 | 1325961 | 0 | 270 | 0.00 | 0.02 | -0.07 | -3.40 |
| 3 | Imperfect | 618583 | 1036285 | 598 | 795 | 0.10 | 0.08 | -1.13 | -2.05 |
| 4 | Moderate | 3762193 | 2589494 | 10983 | 4876 | 0.29 | 0.19 | 0.05 | -1.16 |
| 5 | Good (well drained) | 8012119 | 17080575 | 22716 | 55407 | 0.28 | 0.32 | 0.07 | 0.33 |
| Induration | | | | | | | | | |
| Class# | Description | Total area/ pixels | | Landslide area/ pixels | | Frequency ratio (%) | | Total weight ($W_i$) | |
| | | **East** | **West** | **East** | **West** | **East** | **West** | **East** | **West** |
| 1 | Non-indurated | 353792 | 154290 | 241 | 40 | 0.07 | 0.03 | -1.77 | -2.37 |
| 2 | Very weakly indurated | 92170 | 1620820 | 148 | 280 | 0.16 | 0.02 | -0.89 | -2.84 |
| 3 | Weakly indurated | 938542 | 10784426 | 2135 | 19003 | 0.23 | 0.18 | -0.55 | -0.72 |
| 4 | Strongly indurated | 11381077 | 4693626 | 32014 | 14488 | 0.28 | 0.31 | 0.08 | 0.16 |
| 5 | Very strongly indurated | 11052 | 5401027 | 1 | 27703 | 0.01 | 0.51 | -3.76 | 0.95 |
| High intensity rainfall | | | | | | | | | |
| Class# | Description (24hr rainfall during a 10 year storm event) | Total area/ pixels | | Landslide area/ pixels | | Frequency ratio (%) | | Total weight ($W_i$) | |
| | | **East** | **West** | **East** | **West** | **East** | **West** | **East** | **West** |
| 1 | 0-150mm | 272059 | 4898020 | 137 | 7769 | 0.05 | 0.16 | -0.03 | -0.15 |
| 2 | 150-200mm | 783266 | 6371719 | 1664 | 16705 | 0.21 | 0.26 | -0.27 | -0.09 |
| 3 | 200-250mm | 1753813 | 6447272 | 6161 | 25256 | 0.35 | 0.39 | 0.30 | 0.52 |
| 4 | 250-300mm | 3366567 | 2964520 | 8969 | 7434 | 0.27 | 0.25 | -0.03 | -0.13 |
| 5 | 300-350mm | 2382386 | 1299735 | 6223 | 2401 | 0.26 | 0.18 | -0.05 | -0.45 |
| 6 | 350-400mm | 1449785 | 326986 | 5188 | 850 | 0.36 | 0.26 | 0.31 | -0.09 |
| 7 | 400-450mm | 1338952 | 251545 | 3804 | 1040 | 0.28 | 0.41 | 0.05 | 0.38 |
| 8 | 540-500mm | 1065813 | 129445 | 2123 | 262 | 0.20 | 0.20 | -0.34 | -0.34 |
| 9 | 500-609mm | 394131 | 38629 | 439 | 52 | 0.11 | 0.13 | -0.92 | -0.75 |

| Land cover | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Class# | Description | Total area/ pixels | | Landslide area/ pixels | | Frequency ratio (%) | | Total weight ($W_i$) | |
| | | **East** | **West** | **East** | **West** | **East** | **West** | **East** | **West** |
| 1 | Exotic forests | 1217 | 722542 | 3 | 139 | 0.25 | 0.02 | -0.37 | -3.35 |
| 2 | Freshwater and saline vegetation | 4743 | 306789 | 1 | 2 | 0.02 | 0.00 | -2.83 | -6.72 |
| 3 | Infrastructure | 1245 | 60834 | 10 | 100 | 0.80 | 0.16 | 0.81 | -1.18 |
| 4 | Indigenous forests | 6653501 | 17713801 | 24687 | 55677 | 0.37 | 0.31 | 0.55 | 0.27 |
| 5 | Alpine areas | 3412278 | 319173 | 7164 | 2129 | 0.21 | 0.67 | -0.61 | 0.25 |
| 6 | Mixed shrublands | 19107 | 439157 | 87 | 378 | 0.46 | 0.09 | 0.24 | -1.84 |
| 7 | Pasture land | 129814 | 2507640 | 445 | 1679 | 0.34 | 0.07 | -0.04 | -2.17 |
| 8 | Tussock grasslands | 2585488 | 659605 | 2315 | 1693 | 0.09 | 0.26 | -1.54 | -0.73 |
| Proximity to faults | | | | | | | | | |
| Class # | Description | Total area/ pixels | | Landslide area/ pixels | | Frequency ratio (%) | | Total weight ($W_i$) | |
| | | **East** | **West** | **East** | **West** | **East** | **West** | **East** | **West** |
| 1 | 0-100m | 871363 | 756887 | 2722 | 2072 | 0.31 | 0.27 | 0.13 | 0.01 |
| 2 | 100-1000m | 5233204 | 5610351 | 15985 | 16026 | 0.31 | 0.29 | 0.19 | 0.07 |
| 3 | 1000-3000m | 3966856 | 8046220 | 10490 | 23921 | 0.26 | 0.30 | -0.06 | 0.14 |
| 4 | 3000m+ | 2735383 | 8308985 | 5511 | 19736 | 0.20 | 0.24 | -0.39 | -0.21 |

As seen in table 5.1, some of the factors show much more relation with the occurrence of landslides than others. Where $W_i$ values are close to zero, the factor has little influence on the occurrence of landslides (Van Westen *et al.*, 2003). For example the $W_i$ values for the different classes of the slope aspect (east) factor map oscillate around zero, with no very high or very low values (maximum 0.31 for easterly slopes and minimum -0.50 for south westerly slopes), thus showing that slope aspect is not a very important variable in landslide occurrence. By contrast, the $W_i$ values in the geology (east) factor map, have a maximum of 1.18 for high grade metamorphics and a minimum of -1.06 for fine grained sediments, representing a much wider range of values. Thus, in this example geology shows a greater influence on the occurrence of landslides than aspect.

Interestingly, there are some major differences between the calculated $W_i$ values from the two (east and west) sub-units of the study area. For example, in the land-cover factor map, results show that alpine areas (comprising sub alpine shrub-land, alpine grass-land, alpine herb-land, alpine gravel and rock) are a moderately positive influence ($W_i$ =0.25) on the occurrence of landslides in the western area, whereas alpine areas are a relatively strong negative influence ($W_i$ =-0.61) on the occurrence of landslides in the eastern area. Similarly, in the case of the geology factor map, it seems that the role of the geology classes is different from one side of the Alpine fault to the other. It is for reasons such as this that the study area was separated into the area east of the Alpine fault and the area west of the alpine fault.

## 5.3 Calculation of layer weights using the AHP

Table 5.2 is a pair-wise comparison matrix, which is used to establish the relative importance of each factor map.

**Table 5.2.** Pair-wise comparison matrix used to define the priority weights for the factor maps.

| | Aspect | Drainage | Geology | HIRDS | Induration | Land cover | Proximity to faults | Slope |
|---|---|---|---|---|---|---|---|---|
| Aspect | 1 | 0.5 | 0.125 | 0.333 | 0.5 | 0.333 | 0.333 | 0.125 |
| Drainage | 2 | 1 | 0.333 | 0.5 | 1 | 0.5 | 0.5 | 0.2 |
| Geology | 8 | 3 | 1 | 2 | 2 | 2 | 3 | 0.5 |
| HIRDS | 3 | 2 | 0.5 | 1 | 2 | 0.5 | 0.5 | 0.25 |
| Induration | 2 | 1 | 0.5 | 0.5 | 1 | 0.333 | 0.333 | 0.2 |
| Land cover | 3 | 2 | 0.5 | 2 | 3 | 1 | 1 | 0.333 |
| Proximity to faults | 3 | 2 | 0.333 | 2 | 3 | 1 | 1 | 0.5 |
| Slope | 8 | 5 | 2 | 4 | 5 | 3 | 2 | 1 |
| Priority weights | 0.034 | 0.06 | 0.2 | 0.083 | 0.062 | 0.116 | 0.127 | 0.319 |

From this it can be seen that slope is the most influential factor in the control of landsliding and aspect is the least important factor.

The weights calculated for the various classes within each factor map must now be normalized before further processing. The normalized weights are shown in table 5.3.

**Table 5.3.** Normalized weights ($W_n$) for the various classes in each factor map.

| Class# | Description | Normalized weights ($W_n$) East | Normalized weights ($W_n$) West |
|---|---|---|---|
| **Aspect** | | | |
| 1 | Flat | 0.59 | 0.57 |
| 2 | North | 0.94 | 0.61 |
| 3 | Northeast | 0.98 | 1 |
| 4 | East | 1 | 0.63 |
| 5 | Southeast | 0.63 | 0.48 |
| 6 | South | 0.16 | 0.18 |
| 7 | Southwest | 0 | 0 |
| 8 | West | 0.23 | 0.13 |
| 9 | Northwest | 0.59 | 0.48 |
| **Slope gradient** | | | |
| 1 | 0-10 | 0 | 0 |
| 2 | 10-20 | 0.22 | 0.47 |
| 3 | 20-25 | 0.20 | 0.56 |
| 4 | 25-30 | 0.44 | 0.63 |
| 5 | 30-35 | 0.69 | 0.71 |
| 6 | 35-40 | 0.94 | 0.78 |
| 7 | 40-45 | 1 | 0.86 |
| 8 | 45-50 | 0.97 | 0.93 |
| 9 | 50+ | 0.96 | 1 |
| **Geology** | | | |
| 1 | Quaternary unconsolidated sediments | 0.38 | 0 |
| 2 | Coarse grained sediments | 0.28 | 0.60 |
| 3 | Fine grained sediments | 0 | 0.93 |
| 4 | Granitoids | 0.34 | 0.90 |
| 5 | Mafics and ultramafics | 0.57 | 0.42 |
| 6 | Medium grained sediments | 0.64 | 0.64 |
| 7 | Low to medium grade metamorphics | 0.42 | 0.69 |
| 8 | High grade metamorphics | 1 | 0.62 |

| | | | |
|---|---|---|---|
| 9 | Limestone | N/A | 1 |
| 10 | Peat | 0.56 | 0.02 |
| Drainage | | | |
| Class# | Description | Normalized weights ($W_n$) | |
| | | **East** | **West** |
| 1 | Very poor | 0 | 0.08 |
| 2 | Poor | 0.91 | 0 |
| 3 | Imperfect | 0.22 | 0.36 |
| 4 | Moderate | 0.98 | 0.60 |
| 5 | Good (well drained) | 1 | 1 |
| Induration | | | |
| Class# | Description | Normalized weights ($W_n$) | |
| | | **East** | **West** |
| 1 | Non-indurated | 0.52 | 0.12 |
| 2 | Very weakly indurated | 0.75 | 0 |
| 3 | Weakly indurated | 0.84 | 0.56 |
| 4 | Strongly indurated | 1 | 0.79 |
| 5 | Very strongly indurated | 0 | 1 |
| High intensity rainfall | | | |
| Class# | Description (24hr rainfall during a 10 year storm event) | Normalized weights ($W_n$) | |
| | | **East** | **West** |
| 1 | 0-150mm | 0.72 | 0.47 |
| 2 | 150-200mm | 0.53 | 0.52 |
| 3 | 200-250mm | 0.99 | 1 |
| 4 | 250-300mm | 0.72 | 0.48 |
| 5 | 300-350mm | 0.70 | 0.24 |
| 6 | 350-400mm | 1 | 0.52 |
| 7 | 400-450mm | 0.78 | 0.90 |
| 8 | 540-500mm | 0.46 | 0.32 |
| 9 | 500-609mm | 0 | 0 |
| Land cover | | | |
| Class# | Description | Normalized weights ($W_n$) | |
| | | **East** | **West** |
| 1 | Exotic forests | 0.67 | 0.48 |
| 2 | Freshwater and saline vegetation | 0 | 0 |
| 3 | Infrastructure | 1 | 0.79 |
| 4 | Indigenous forests | 0.93 | 1 |

| | | | |
|---|---|---|---|
| 5 | Alpine areas | 0.61 | 0.99 |
| 6 | Mixed shrublands | 0.84 | 0.70 |
| 7 | Pasture land | 0.77 | 0.65 |
| 8 | Tussock grasslands | 0.35 | 0.86 |
| Proximity to faults | | | |
| Class# | Description | Normalized weights ($W_n$) | |
| | | **East** | **West** |
| 1 | 0-100m | 0.89 | 0.61 |
| 2 | 100-1000m | 1 | 0.78 |
| 3 | 1000-3000m | 0.57 | 1 |
| 4 | 3000m+ | 0 | 0 |

## 5.4 Weighted sum process

To produce a landslide susceptibility index (LSI) map with the weighting factor method (WFM), the factor maps are reclassified, using the weighting values ($W_i$), and then overlayed and numerically added according to equation 5 to produce a landslide susceptibility index map.

$$\mathrm{LSI} = W_{iSlope} + W_{iAspect} + W_{i\mathrm{Geology}} + W_{i\ \mathrm{Land\ cover}} + W_{i\mathrm{HIRDS}} + W_{i\mathrm{Drainage}} + W_i + W_{i\mathrm{Induration}} + W_{i\mathrm{Proximity\ to\ faults}} \quad (5)$$

To produce a landslide susceptibility index (LSI) map with the analytical hierarchy process method (AHP), the factor maps are reclassified, using the normalized weighting values ($W_n$), and then overlayed and numerically added, using the calculated priority weights as multipliers for each layer. This is shown in equation 6.

$$\mathrm{LSI} = (0.319)W_{n\mathrm{Slope}} + (0.034)W_{n\mathrm{Aspect}} + (0.200)W_{n\mathrm{Geology}} + (0.116)W_{n\mathrm{Land\ cover}} + (0.083)W_{n\mathrm{HIRDS}} + (0.060)W_{n\mathrm{Drainage}} + (0.062)W_{n\mathrm{Induration}} + (0.127)W_{n\mathrm{Proximity\ to\ faults}} \quad (6)$$

The resulting LSI maps were then tested using the success rate method of Chung and Fabbri (1999). Since the area to the east of the Alpine fault has been handled separately from the area to the west of the Alpine fault there are four LSI maps to test:

1. LSI map of the Eastern area generated using the weighting factor method (WFM_E).
2. LSI map of the Western area generated using the weighting factor method (WFM_W).
3. LSI map of the Eastern area generated using the analytical hierarchy process method (AHP_E).
4. LSI map of the Western area generated using the analytical hierarchy process method (AHP_W).

## 5.5 Success rate testing

The success rate is calculated by ordering the pixels of the LSI maps and grouping into 100 classes from high to low values, in a quantile distribution based on the frequency information from the histogram of their distribution. After that, the landslide inventory is overlayed with the categorised LSI map and the joint frequency is then plotted on a scatter graph (Chung and Fabbri, 2003; Frattini *et al.,* 2010). A hypothetical success rate curve coinciding with a diagonal from 0 to 100 would be equivalent to a totally random prediction. The further the success rate curve is from that diagonal, the better the predictive value of the map. Likewise, the steeper the gradient in the low % part of the curve the greater its predictive capability (Chung and Fabbri, 2003; Remondo *et al.,* 2003)

The success rate curves shown in figure 5.1 indicate what percentage of all landslides occur in the classes with highest LSI values for the LSI maps from the Western area,

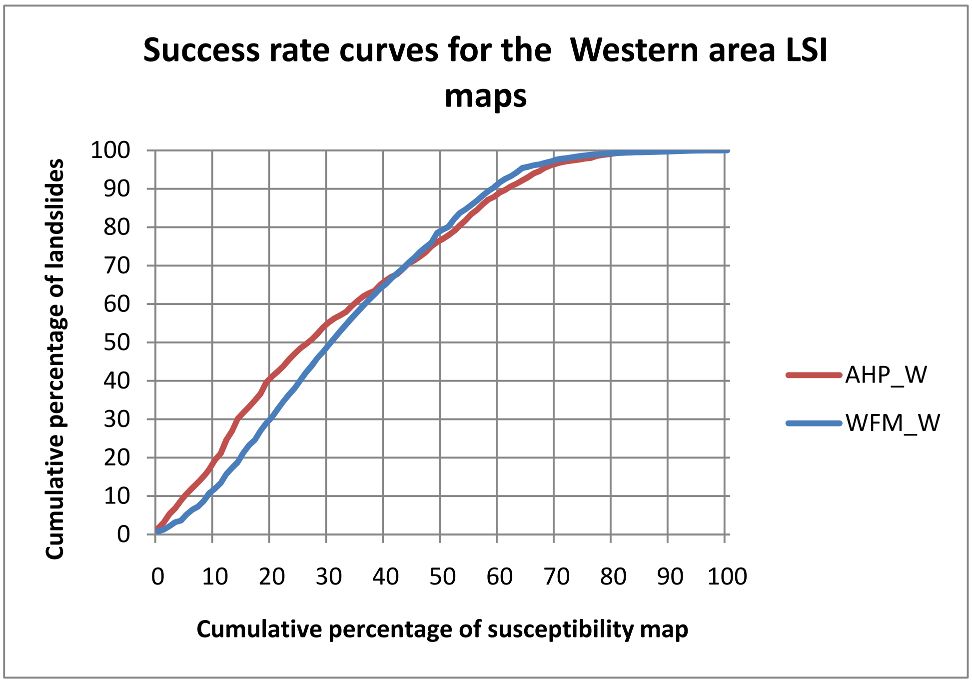



**Figure 5.1.** Success rates calculated for the LSI maps in the area west of the Alpine fault.

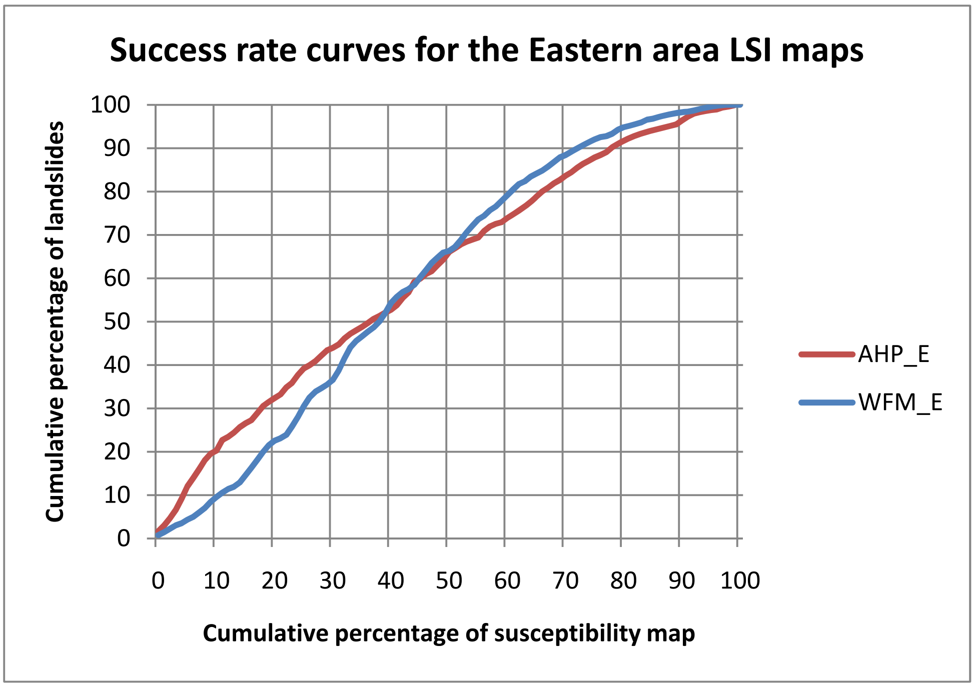



**Figure 5.2.** Success rates calculated for the LSI maps in the area east of the Alpine fault.

and figure 5.2 shows the success rate curves for the Eastern area.

The success rate curve for the LSI map, AHP_W, shows that 40% of all the mapped landslides are predicted by 20% of the classes with the highest values in the LSI map. This is in contrast to the curve for WFM_W, which only predicted 30% of the landslides in the top 20% of the susceptibility classes of the map. Interestingly, the WFM produced marginally more accurate results than the AHP in the upper part of the curve. The area under the curve is comparatively greater for the AHP_W map than the WFM_W map, indicating a greater goodness of fit for the AHP generated map.

As seen in figure 5.2, the AHP generated maps have produced a more accurate LSI map than the WFM. This is exemplified by the fact that 20% of all the landslides were predicted by 10% of the highest susceptibility scores in the AHP_E map, whereas only 10% of the landslides were predicted by the top 10% of the susceptibility scores for the WFM_E map.

When the LSI maps from the Eastern area are compared to the LSI maps from the Western area, the success rate curves of the western LSI maps show a steeper trend and are further from the diagonal than the eastern LSI maps, showing a greater success rate of the model in the western area. The reasoning for this is twofold: firstly, less aerial photography was available in the eastern area, so the accuracy of the landslide inventory layer for this area will be poorer than the western area. This deficiency of input data has obviously affected the quality of the outputs. In addition to this, the area of very low slope gradient (flat land) is much smaller in the eastern area, so consequently the landslide distribution is more uniform in comparison to the western area, which has a large area, essentially free of landslide hazard. This is discussed further in chapter 7.

## 5.6 Validation

The mapped landslides visible on the newly-obtained aerial photography were digitised into a GIS and overlayed with the LSI maps. Prior to this, the susceptibility scores on each map were reclassified in a scale of 1 to 100 in a quantile distribution according to the raster’s histogram. The landslide areas were then extracted from the susceptibility map and the pixels ordered from low to high susceptibility. The predictive success rates are presented in figure 5.3 and were plotted in the same manner as the success rate testing. It provides a quantitative indication of the susceptibility map to match the known distribution of landslides in the validation area (Guzzetti *et al.,* 2006).

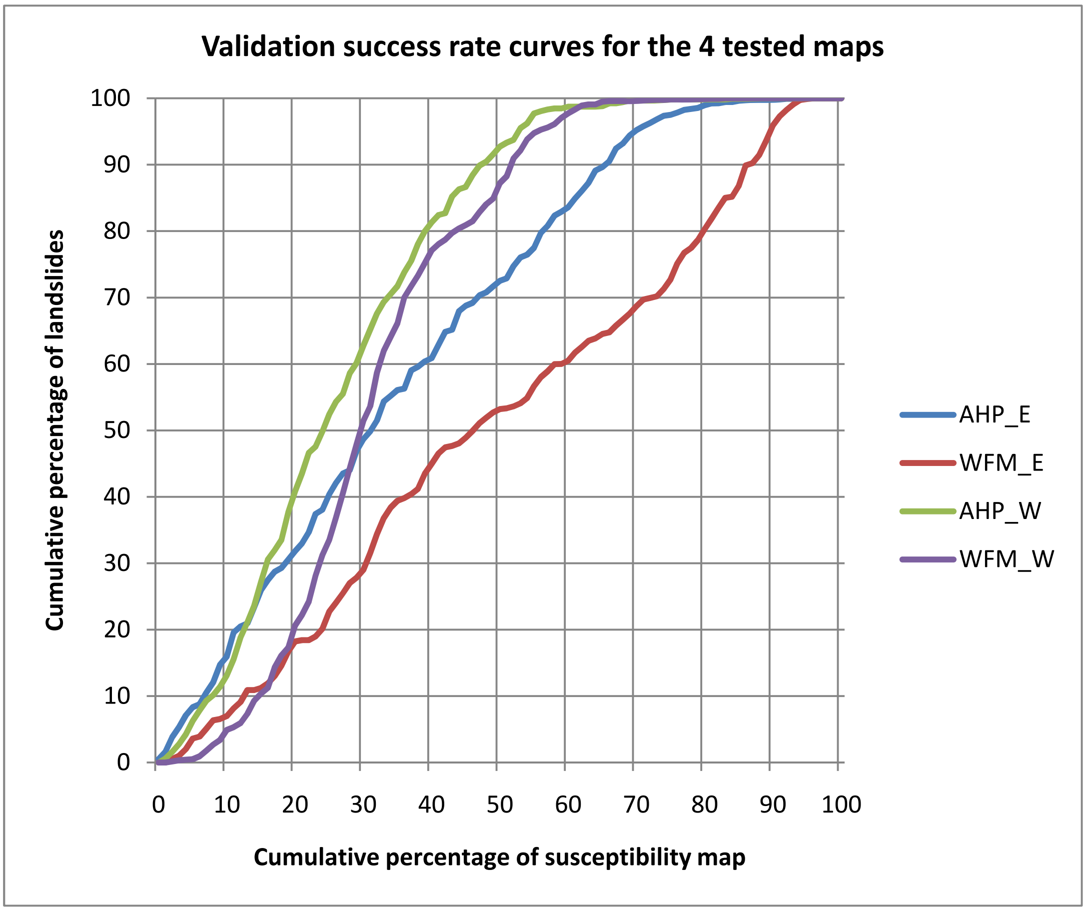



**Figure 5.3.** Validation success rate curves for the 4 tested maps.

From this it can be seen that in the case of AHP_W, 40% of the landslides occurred in 20% of the map with the highest susceptibility values and 80% of the landslides occurred in 40% of the map with the highest susceptibility scores.

The susceptibility maps for the eastern area (Southern Alps) show a marginally better fit than the western maps in the first part of the curve, but towards the ends of the curves it is clear that the eastern maps do not perform as well. For example, in the case of both western maps, all the validation landslides (100%) occurred in 70%

of the map, but for the case of the eastern maps there were still landslides occurring in the lowest 10% of the susceptibility classes.

The area under the curve for the AHP maps is noticeably larger than for the WFM maps, which proves the superior predictive capability of the AHP method in generating landslide susceptibility maps. On the basis of these results, the most appropriate maps to use for landslide hazard management in the West Coast region are the ones generated using bivariate statistics and the analytical hierarchy process.

## 5.7 Assigning susceptibility zones

For the purposes of validating the maps the susceptibility scores were reclassified in a scale of 1-100. This is useful for interrogating the predictive power of the maps. However, the usefulness of a susceptibility map is greatly increased when it is divided into 5 zones: very low, low, moderate, high and very high susceptibility to landsliding (Fell *et al.*, 2008). This zoning is accomplished by assigning LSI values to the boundaries between the zones such that a certain proportion of the mapped landslides fall within each zone. This gives a quantitative value to the susceptibility map zones and is therefore useful in providing the end user with relative landslide probabilities. Once the zones are established, further interrogation of the map is possible and values relating to landslide density and total landslide counts for each zone can be presented thus enhancing the quantitative aspects of the map.

By extracting the all the landslide polygons (from the original dataset and the validation dataset) from the LSI map and ordering those pixels from high to low it is possible to find the corresponding LSI value that relates to a certain percentage of landslides. Table 5.4 shows the percentage of landslides and the LSI values that were used to assign the zones to the final susceptibility map. So, 70 % of landslides occur in the very high susceptibility zone, 22% in the high susceptibility zone, etc.

**Table 5.4.** Percentage of landslides in each susceptibility zone and their corresponding LSI values.

| Susceptibility zone | Percentage of all landslides | LSI values | |
|---|---|---|---|
| | | East | West |
| Very low | 1 | 0-7 | 0-24 |
| Low | 2 | 8-15 | 25-33 |
| Moderate | 5 | 16-29 | 34-44 |
| High | 22 | 30-58 | 45-70 |
| Very high | 70 | 59-100 | 71-100 |

Figure 4.4 (page 77) illustrates the difference between an LSI map, showing a continuous variable of landslide susceptibility index scores and a susceptibility map, which has 5 distinct zones.

Once the zones are established the spatial characteristics of these can be explored which will help in the final use of the susceptibility map.

## 5.8 Spatial characteristics of the landslide susceptibility zones

In order for the susceptibility map to be understood and utilized properly for landslide hazard management purposes, it is necessary to explain some of the characteristics of the zones. Table 5.5 illustrates the spatial distribution of the 5 susceptibility zones. It is worth noting here that 34% of the area to the east of the Alpine fault is classed as “very high” susceptibility to landsliding, whereas the corresponding zone on the western side of the fault is only 24% of the land area. This is in accordance with the initial expectations.

**Table 5.5.** Area of the region covered by the different susceptibility zones.

| Susceptibility zone | % of eastern area of West Coast Region | % of western area of West Coast Region | % of West Coast region |
|---|---|---|---|
| Very low | 5.7 | 27.2 | 19.5 |
| Low | 9.6 | 11.1 | 10.6 |
| Moderate | 18.1 | 11.6 | 14.0 |
| High | 32.6 | 25.8 | 28.3 |
| Very high | 34.0 | 24.3 | 27.8 |

Further analysis of the spatial characteristics of the map is useful to define the meanings of the zones. Table 5.6 shows the land area, landslide density and % of the land surface affected by landslides in each zone.

**Table 5.6.** Spatial characteristics of the landslide susceptibility zones.

| Susceptibility zone | Area/$km^2$ | Landslide density: number of landslides/$10km^2$ | % of land surface affected by landslides |
|---|---|---|---|
| Very low | 4302 | 0.0 | 0.003 |
| Low | 2334 | 0.3 | 0.012 |
| Moderate | 3085 | 0.6 | 0.056 |
| High | 6256 | 1.5 | 0.218 |
| Very high | 6145 | 3.8 | 0.513 |

Since the landslide inventory is necessarily incomplete (see chapter 3) these figures are an underestimation and the actual rate of landslide occurrence may be much higher than this. The true value of the susceptibility zones is realised when local knowledge of landslide occurrence is combined with the thresholds described in tables 5.4, 5.5 and 5.6, and the zones are then used in a comparative sense.

## 5.9 Limitations

By definition, a landslide susceptibility map does not make any attempt to define the temporal characteristics of the occurrence of landslides (Fell *et al.*, 2004). Since timeframe is an essential part of the risk equation, a susceptibility map should not be used for detailed risk assessments.

This is a regional scale study and should be used as such. The scale used for the initial landslide mapping was 1:25,000 so the susceptibility maps should be viewed at that scale. The minimum mapping unit in this study is the 25m x 25m pixel, so this mapping roughness should also be taken into account when using the susceptibility map.

Any landslide susceptibility study has a certain level of uncertainty (Guzetti *et al.*, 2006). Sources of uncertainty include:

- Errors and incompleteness in the landslide inventory
- Errors in the thematic factor maps
- Limitations in the technique chosen for the susceptibility analysis
- The inherent natural variability of the landslide phenomena

At best, the present model has an accuracy that predicts 80% of the landslides in the top 40% of the susceptibility scores. However, the model cannot claim to accurately delineate the probability of occurrence in each of the susceptibility zones.

A susceptibility map is useful for a first pass review of landslide hazard, and can be used to feed into land use and development decisions.

# Chapter 6. From landslide hazard information to landslide hazard management

## 6.1 Introduction

Before the losses from landslides can be reduced, the hazard must first be recognised and the risk assessed appropriately (Saunders and Glassey, 2007). This study has assessed the landscape’s susceptibility to rainfall-generated landsliding and displayed this on a landslide susceptibility map. It has also collated information relating to past landsliding in the West Coast region in the form of a landslide catalogue. As one of the primary thesis objectives these two tools have been delivered to the decision-makers of the region, enabling the hazard information contained in this study to be effectively used for landslide hazard management. To achieve this, a “user manual” has been produced and delivered to the decision-makers of the region via a series of educational workshops. This chapter outlines this process.

Also, by means of a case study, the hazard information is combined with the position and use of buildings and infrastructure in the area between Waimangaroa and Nikau, Buller district. A preliminary risk assessment is made and suggestions for action and further research are proposed.

## 6.2 Context

New Zealanders aspire to live in communities that are vibrant, sustainable, and resilient to natural hazards. This is reflected in and facilitated by legislation including the Resource Management Act (RMA), the Local Government Act (LGA) and Civil Defence Emergency Management Act (CDEMA). As is now widely recognised, land-use planning has a critical role to play in realising this vision and is essential in translating the legislative and policy intentions into practical reality (Glavovic, *et al.,* 2010; Saunders and Glassey, 2007; Glavovic, 2010). Broadly, the RMA requires Regional and District Councils to identify and avoid or mitigate natural hazards via a self managed suite of policies, plans and building and land-use consent approval processes. The CDEMA supports these planning provisions and aims to build community resilience, through the implementation of the reduction, readiness, response and recovery (4R's) emergency management framework (Glavovic, 2010). When viewed as a whole, these legislative provisions and the hazard information contained in this study provide a solid practical, policy and legal foundation which will enable local government planners to avoid or mitigate landslide hazard risks and help develop sustainable, hazard-resilient communities in the West Coast region.

In 2007 GNS Science published the "Guidelines for assessing planning policy and consent requirements for landslide prone land" (Saunders and Glassey, 2007), which has become the standard reference document for Council Planners in matters relating to landslide hazard management. It sets out a simple strategy based on 4 principles:

1. **Gather accurate landslide hazard information**
   Identifying the areas prone to landsliding and plotting these on a map is the first step in communicating the risk posed by landsliding. Because the existence (or likelihood of occurrence at a given location) of a landslide will have an effect on the decision to buy or build on a property, all information on the landslide hazard should be as accurate as knowledge, technical standards and resources permit.
2. **Plan to avoid landslide hazards before development and subdivision**
   Preventing building and development on known landslide hazard areas is the simplest and cheapest method of landslide hazard avoidance. Where this is not achievable, mitigation measures should be investigated and implemented so that the risk is reduced to an acceptable level. Risk avoidance is the safest long term solution and can often be achieved at little or no extra cost.
3. **Take a risk-based approach in areas already developed or subdivided**
   This involves identifying the nature of the hazard and assessing the consequences to the elements at risk. Once this is established, the question of whether or not this risk is acceptable needs to be answered. This leads to the risk management phase, where actions are taken to treat the risk. Figure 6.1 illustrates the risk-based planning approach detailed in AS/NZS Risk Management Standard 4360:2004.

Where land has been subdivided there is an expectation that building on these sites will be allowed. However, as new hazard information becomes available it is still the responsibility of the local authority when considering building consent applications to take this information into account.

4. **Communicate the risk of landslides in built-up areas**

   The risk of building in landslide-prone areas may be obvious now, but historically this may not have been the case, therefore structures may have been built in inappropriate locations. The ideal approach here is to avoid further development in high-risk areas, limit existing land use rights to rebuild, and limit the use of buildings. However, a more realistic approach is to accept the status quo and ensure that any further developments are consistent with the level of risk posed, and that the district plan clearly shows the landslide hazard zones.

   Hazard education programmes and incentives to retire at-risk land may also be utilised to ensure that occupiers are aware of the landslide risk and encouraged to take the appropriate action (from Saunders and Glassey, 2007)

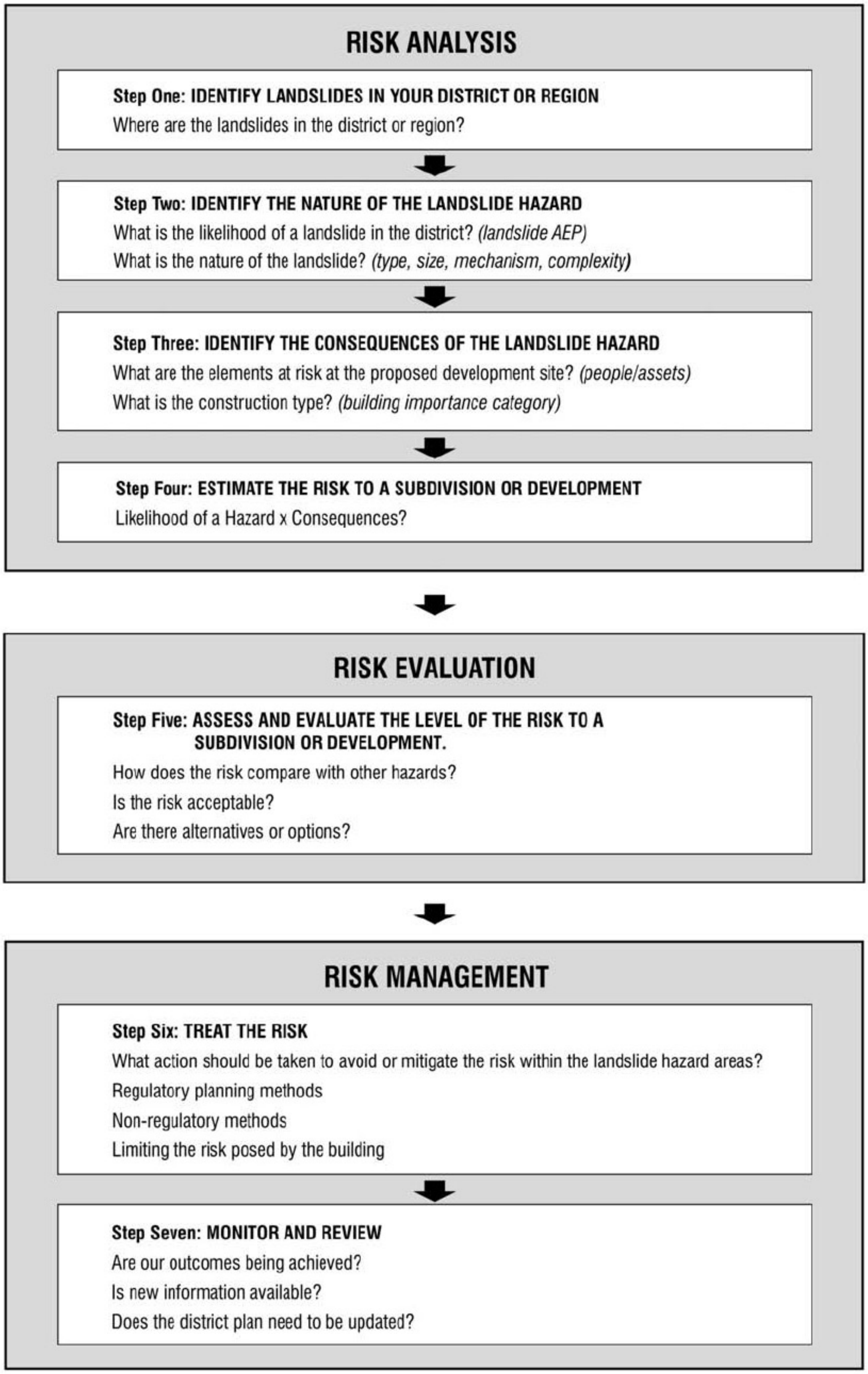



**Figure 6.1.** Risk-based planning approach of AS/NZS Risk Management Standard 4360:2004 (Saunders and Glassey, 2007).

This study has already addressed the first of these principles by developing a landslide susceptibility map and landslide catalogue. This chapter also illustrates the application of this hazard information to the avoidance and risk based approaches to landslide hazard management.

## 6.3 Transferring the landslide hazard information to the decision-makers of the region

In order to make the information contained within this thesis readily available for use by the decision-makers of the region a manual entitled “A landslide susceptibility map and landslide catalogue for the West Coast region-the user guide” (see appendix B) was produced and delivered to the following groups via a series of educational workshops:

- The West Coast Engineering Lifelines Group
- The Planning, Consents, Natural hazards and Civil defence staff at West Coast Regional Council
- Building consents and Compliance staff at Buller District Council
- Building consents and Compliance staff at Grey District Council
- Building consents and Compliance staff at Westland District Council
- Planning and Concessions staff at Department of Conservation, West Coast Conservancy.

The manual and educational workshop explains the methodology used to produce the landslide susceptibility map and landslide catalogue. It also explains the level of confidence to apply to these tools, and their usefulness and limitations. It shows how the hazard information can be used, in conjunction with existing guidelines, to manage the landslide hazard in the West Coast region.

## 6.4 The landslide susceptibility map and landslide catalogue in a planning context

The landslide susceptibility zones, when used in combination with asset information held at the councils, will be useful in making land-use change decisions. For example, different levels of hazard can be acceptable to various elements at risk depending on the consequences of a landslide occurring at a particular site (Saunders and Glassey, 2007). To classify buildings, in terms of elements at risk, a Building Importance

Category (BIC) classification is one option that can be used. The most appropriate system is the Australia/New Zealand Standard for Structural Design Actions, General Principles (AS/NZS 1170.0:2002). This is illustrated in table 6.1. This classification does not cover roads, bridges, or other essential infrastructure, but these items could be placed into a BIC category based on the relative importance of the item in question.

**Table 6.1** Building Importance Categories: a modified version of New Zealand Loading Standard classifications (AS/NZS 1170.0:2002). Taken from Saunders and Glassey, 2007.

| Building Importance Category (BIC) | Description | Examples |
|---|---|---|
| 1 | Low consequence for loss of human life, or small or moderate economic, social, or environmental consequences. | Structures with a total floor area of less than 30m2<br>Farm buildings, isolated structures, towers in rural situations<br>Fences, masts, walls, in-ground swimming pools |
| 2a | Medium consequence for loss of human life, or considerable economic, social, or environmental consequences | Timber framed single-storey dwellings |
| 2b | (As above) | Timber framed houses of plan area more than 300m2<br>Houses outside the scope of NZS3604 “Timber Framed Buildings”<br>Multi-occupancy residential, commercial (including shops), industrial, office and retailing buildings designed to accommodate less than 5,000 people and also those less than 10,000m2 gross area.<br>Public assembly buildings, theatres and cinemas of less than 1000m2<br>Car parking buildings |

| Building Importance Category (BIC) | Description | Examples |
|---|---|---|
| 3 | High consequence for loss of human life, or very great economic, social, or environmental consequences (affecting crowds) | Emergency medical and other emergency facilities not designated as post disaster facilities<br>Buildings where more than 300 people can congregate in one area<br>Buildings and facilities with primary school, secondary school or day care facilities with capacity greater than 250<br>Buildings and facilities with capacity greater than 500 for colleges or adult education facilities<br>Health care facilities with a capacity of 50 or more residents but not having surgery or emergency treatment facilities<br>Airport terminals, principal railway stations, with a capacity of more than 250 people<br>Any occupancy with an occupancy load greater than 5,000<br>Power generating facilities, water treatment and waste water treatment facilities and other public utilities not included in Building Importance Category (BIC) 4<br>Buildings and facilities not included in BIC 4 containing hazardous materials capable of causing hazardous conditions that do not extend beyond the property boundaries |
| 4 | High consequence for loss of human life, or very great economic, social, or environmental consequences (post disaster functions) | Buildings and facilities designated as essential facilities<br>Buildings and facilities with special post-disaster function<br>Medical emergency or surgical facilities<br>Emergency service facilities such as fire, police stations and emergency vehicle garages<br>Utilities required as backup for buildings and facilities of importance level 4<br>Designated emergency shelters<br>Designated emergency centres and ancillary facilities<br>Buildings and facilities containing hazardous materials capable of causing hazardous conditions that extend beyond the property boundaries |

| Building Importance Category (BIC) | Description | Examples |
|---|---|---|
| 5 | Circumstances where reliability must be set on a case by case basis | Large dams, extreme hazard facilities |

AS/NZS 1170.0:2002 outlines design criteria for the different BIC's based on a risk estimation procedure. Risk is defined as the combination of the likelihood (probability) of an event and the consequences (damages and/or loss of lives) of a particular hazard. Since the landslide susceptibility map explicitly does not take-time frame into account it does not display probabilities, so cannot be used for a detailed risk assessment. However, it can be used a guideline for potential new developments, or to highlight potential problem areas.

Table 6.2 defines the susceptibility zones in terms of landslide potential. It also gives suggested actions. However, any regulations and rules to apply to each of the zones must be decided on by the Regional or District Councils, as this requires local knowledge of risk acceptance (tolerance) levels and will be a function of agreed local government policy.

**Table 6.2.** Meanings and suggested actions relating to the five landslide susceptibility zones.

| Susceptibility zone | Meaning | Suggested action |
|---|---|---|
| Very low | Effectively free of landslide hazard | Building and other activities need not take landslide hazard into account |
| Low | Landslides occur infrequently and will be small and easily managed | Building and other activities need only consider landslides as a minor threat |
| Moderate | Landslides occur infrequently, but on rare occasions may be large enough to cause property damage | Landslide hazard should be considered when planning a development, but need not be a restrictive concern, except where the proposed activity has high consequence for loss of life. For example, BIC 3, 4 or 5 |
| High | Damaging landslides occur occasionally and smaller landslides may be frequent | Building should be restricted to BIC 1 and 2a. A safe building site should be identified and mitigative measures designed by a suitably qualified person. Existing property owners in this zone should be notified of and educated about the hazard |
| Very high | Damaging landslides are common | Building should be restricted to BIC 1. Existing property owners in this zone should be notified of the landslide hazard and encouraged to take mitigative or avoidance actions |

This landslide hazard information should be included in Regional and District Plans. Rules can be applied to each of the susceptibility zones to control various aspects of development in landslide-prone areas, including design, construction, location, usage and density. These rules need to relate to the avoidance or reduction of exposure to landslide hazard (Saunders and Glassey, 2007). It can also be used to guide the regional development plan to avoid the development of landslide-prone land and encourage the use of land shown as very low or low susceptibility to landslides.

When viewing the landslide susceptibility map, it is also useful to view the landslide inventory layers. These display the outlines of the disturbed areas of all the rainfall-triggered landslides that were used to construct the model, and the mapped outlines of the large landslides triggered by earthquake and other means.

The landslide catalogue, when displayed in a GIS, can be queried to display all the recorded damaging landslides that have occurred in a specific area. This is useful in the early stages of an investigation to characterise the types, frequency and damages caused by landslides in that area. Further analysis of these landslide data is then possible to give probabilities of occurrence, rainfall amount trigger levels, etc. for some areas.

The landslide susceptibility map and the landslide catalogue should be used as a "first pass" assessment of landslide potential for an area of interest. This may be enough to persuade a potential developer to look for an alternative site, or to consider modification of development plans. They can also be used as supporting evidence for expert based geotechnical investigations.

Other potential uses of the landslide catalogue and susceptibility map include:

- Selection of suitable positions of power poles for new electricity transmission lines
- Planning the routes and design considerations for other lifelines
- Civil defence planning for heavy rainfall events
- Backcountry activity risk assessments
- Preliminary guidance for new road alignment
- Guidance on other land use changes

## 6.5 Landslide hazard management in the West Coast region. A case study

### 6.5.1 The study area: characteristics and a brief history.

At the request of the West Coast Regional Council, the area of coastal development from Waimangaroa to Nikau was chosen as a study area to illustrate the usefulness of the regional susceptibility map and the newly compiled landslide catalogue in landslide hazard management. Figure 6.2 shows the location of the study area.

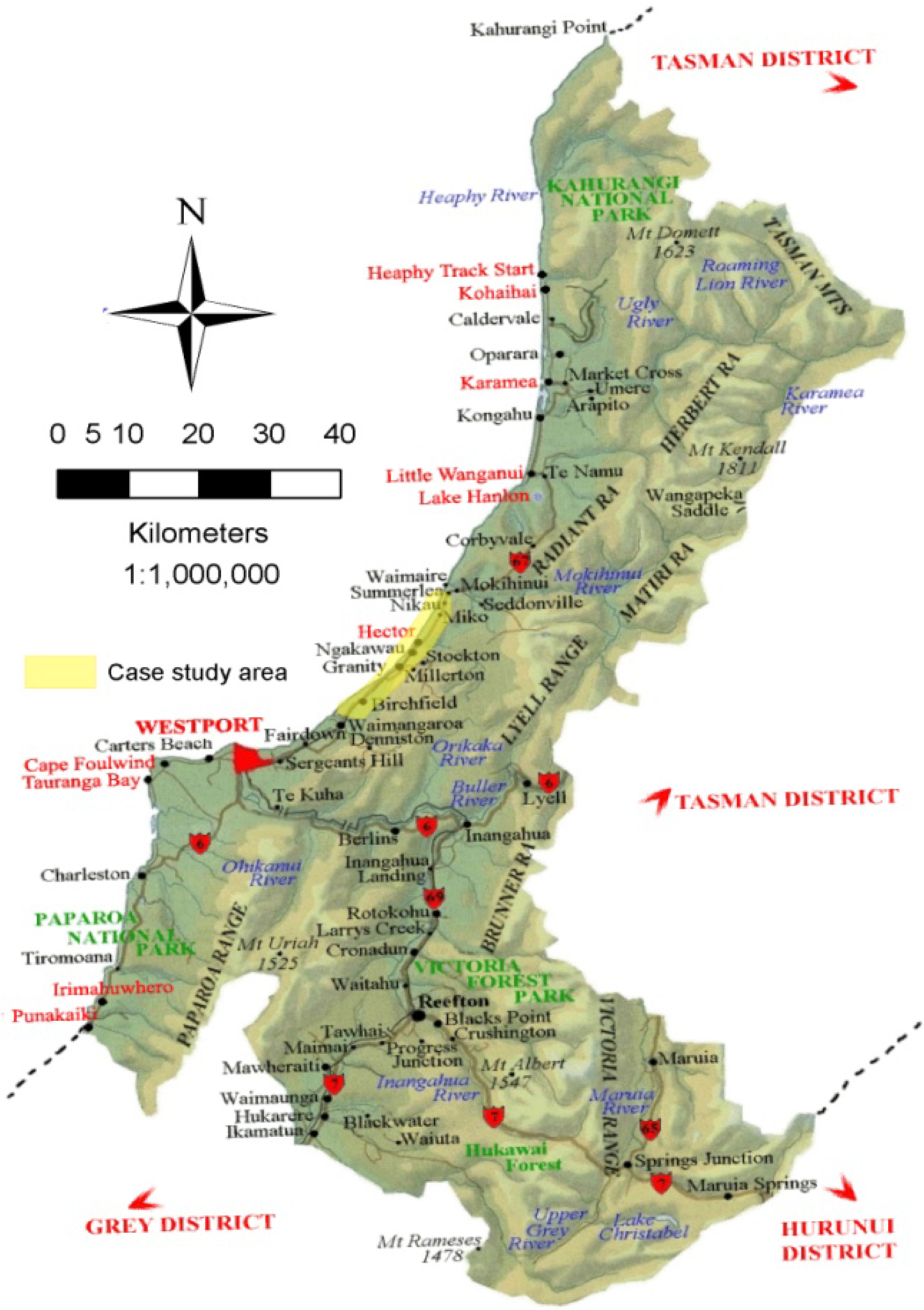



**Figure 6.2.** Location of the study area (from West Coast Web, 2007).

Figure 6.3 is an oblique aerial photograph showing the study area looking north from Waimangaroa towards Granity and Nikau in the distance, with the Kongahu fault marked in red.


**Figure 6.3.** Aerial view of the study area looking north along the range-front. Photo: DOC.

The 2009 statistical profile of the Buller District (Buller District Council, 2009), reports that the population of the Ngakawau-Hector area fell from 357 in 1996 to 234 in 2006 and the population of Granity fell from 315 in 1996 to 219 in 2006. It also reports that the towns of Granity and Ngakawau-Hector have the highest median age (45 years) of any area of the District. In addition to this, the socio-economic profile of the District shows that the residents of Buller District are markedly more deprived than the country's population as a whole. The towns of Granity, Ngakawau and Hector being described as among the 10% of the most deprived areas in New Zealand, with mean annual incomes of $13,500 in Granity and $14,000 in Ngakawau-Hector. In 2006, 40% of the District's adults had no educational qualifications – a far larger proportion than the 25% nationally. This is reflected in the fact that in all but two years from 1993 to 2007, the proportion of students leaving Buller High School with little or no formal attainment was higher than nationally. In 2006 37% of school leavers from Buller High School had little or no formal attainment (Buller District Council, 2009).

Historically, residential development has been concentrated at the base of the range-front in close proximity to the Stockton and Millerton coal mines. Unpredictable and often severe rates of coastal erosion have routinely affected the townships of Ngakawau-Hector and Granity (Ramsay, 2006; 2007). This may have encouraged the developments to spread as close (as far from the sea) to the range-front as possible. More recently, many new developments have taken advantage of elevated sections with fine coastal views and stunning north-westerly outlooks, putting residential houses and baches high on alluvial fans, and steep hillsides.

Figure 6.4 shows historic developments in Granity and newer "lifestyle" type developments at Lamplough Stream, just south of Nikau.

**Figure 6.4.** Examples of developments at the base of the steep fault-bounded range-front at Granity (left) and Lamplough Stream (right). Photo's: DOC.

The Kongahu fault is a zone of major thrust faulting trending SW-NE along the base of the Stockton Plateau escarpment (Todd, 1989). Throw is unknown, but considerable (Todd, 1989) and has uplifted the granite basement rocks creating steep, north-westerly aspect slopes with dense vegetation cover. The Kongahu fault zone extends the entirety of the study area and acts as a range-bounding feature at the base of the range-front. The soils on the hillsides are generally shallow, well drained, with poor induration and cohesion, the underlying rocks exhibiting varying degrees of fault zone weakening (Nathan *et al.,* 2002).

Landsliding is common. Frequent heavy rainfall commonly triggers shallow landslides, which have caused damage to many houses in the study area as well as frequent interruptions to road and rail travel. Debris slips and debris flows are often caused by the increased weight of a soil on a steep slope due to rainwater infiltration, combined with the increased pore fluid pressure and decreased cohesion associated with the heavy rain and infiltration. Debris slips are most commonly associated with heavy rainfall and under the right rheological and hydrological conditions can transform into debris flows. Debris flows are by far the most damaging form of landslide, often travelling at great speed and having large run-out distances (Gabet and Mudd, 2006).

The Buller District Council has identified three areas which are at risk from landslides (Buller District Council, 2000):

1. Little Wanganui Subdivision, which is exposed to rockfall and debris-flow hazards, and the residents have indicated a willingness to accept the risks associated with this hazard.
2. Punakaiki, where some of the township is threatened by rockfall.
3. The coastal strip between Hector and Miko, which is prone to rockfall and rapid debris flow.

The Buller District Plan (Buller District Council, 2000) also recognises that “many areas of the District could be affected by slumping or falling rocks, especially if the land surface were disturbed by building works”. In recognition of the landslide hazard between Hector and Miko this area has been designated as a “rockfall and rapid debris flow hazard zone” (Buller District Council, 2000). This area was declared on 9$^{th}$ of March 1996 after a series of landslides caused property damages in the area in 1995. The area is illustrated on maps in the District Plan. However, the methodology behind the designation is unknown and hence the rules applied to this area are vague (*pers. comm.* Richard Knudson, Senior Building Inspector, BDC). The “rockfall and rapid debris flow hazard area” is illustrated in figures 6.9 and 6.10.

The Land Information Memoranda (LIM) for properties in this area state that the properties are subject to Section 73 of the Building Act 2004. This requires that:

1. The District Land Registrar makes an entry on the Certificate of Title stating that the building consent was issued under Section 73 of the Building Act.
2. A geotechnical engineer's report identifying a safe building and effluent disposal site must be received.

Property owners are also advised that they should discuss the ramifications of building on hazardous land with their insurance company and the Earthquake Commission. (Buller District Council, 2000).

In respect to an application for subdivision of parcels within this "rockfall and rapid debris flow hazard zone", the Buller District Plan (Buller District Council, 2000) states that "The applicant will be required to supply Council with a geotechnical hazard report from a suitably qualified person. The report should assess the land in relation to a 100 year hazard including any mitigation measures. Note: if the land in question is entirely within the 100 year hazard line, Council may decline the subdivision consent".

Prior to the 1995 designation of the hazard zone, various properties were built, many of which are in potentially hazardous locations. Figure 6.5 shows a property built prior to 1995, which was not required to supply a geotechnical hazard report. Since a geotechnical hazard report was not required, no mitigation measures were built. Consequently, the property may be highly prone to damage from landslides.

**Figure 6.5.** Property built prior to 1995 that did not require a geotechnical hazard report. Photo: Author.

Since 1995, when this designation of hazardous land was made, various existing property owners have expressed their concerns over the devaluation effects on their properties. However, regardless of the hazardous land designation, there have been numerous building consents for residential and commercial premises granted in this zone. Each of these received geotechnical engineer's reports detailing the mitigative measures required to allow the development to go ahead.

There have also been unauthorized building works within this hazard zone. For example, in 2007, a yurt was constructed and inhabited in the hazard zone and subsequently removed after a Notice to Fix was issued, explaining that the structure must be demolished as its construction was an offence under Section 168 of the Building Act 2004 (letter from Richard Knudson to Peter and Rosaline Kimus, 13 March, 2008). The presence of one unauthorised building suggests that more unauthorised buildings may exist within this zone.

In summary, the area between Waimangaroa and Nikau has experienced many landslides in the past. This has led to the designation of a small area between Hector and Miko (in the north of the study area), as a “rockfall and rapid debris flow hazard zone”. Historic developments were often built at the base of landslide-prone slopes and more recently, residences have been built high on alluvial fans and fault scarps. The frequency of small landslides has led to an acceptance of the landslide hazard for many residents of the study area, who are seemingly comfortable to live in close proximity to existing landslides.

### 6.5.2 Methodology and observations

#### 6.5.2.1 Introduction

The first stage in a landslide hazard study such as this is to collate the best available information pertaining to the hazard. By performing a simple spatial query in a GIS the relevant entries can be extracted from the historic landslide catalogue and analysis of these will give a clear picture of the nature of the hazard. After this, the landslide susceptibility map can be used to define avoidance zones in areas where development has not yet occurred. In combination with property boundaries, building footprint and building use information, the landslide susceptibility map can be used to perform a qualitative risk analysis on the elements at risk. Recommendations on actions to be taken as a result of this risk analysis are made, but the issue of risk tolerance and risk acceptance must be approached from a Council governance perspective and therefore lies outside the scope of this study.

#### 6.5.2.2 Past landslides in the study area

A spatial query in a GIS will highlight all the listed damaging landslides within the study area as detailed in the newly compiled (this study) landslide catalogue. These can easily be extracted and displayed in tabular form. Table 6.3 was extracted directly from the landslide catalogue and shows the details of 26 entries for damaging landslides in the study area.

From this it can be seen that landslides have caused 1 death and damaged at least 9 houses, caused many road delays, railway closures, evacuations of 6 houses and other property damage. It must be noted here that this catalogue is only a representation of the complete picture of landslide occurrences in the study area as it relies on reporting of incidents, which may not be complete. It can therefore be assumed that the actual damages caused by landsliding in the study area are higher than reported here.

Further analysis of the catalogue data reveals that the most common form of landslide to cause damage in the study area is a debris slip. Figure 6.6 shows the distribution of landslide types.

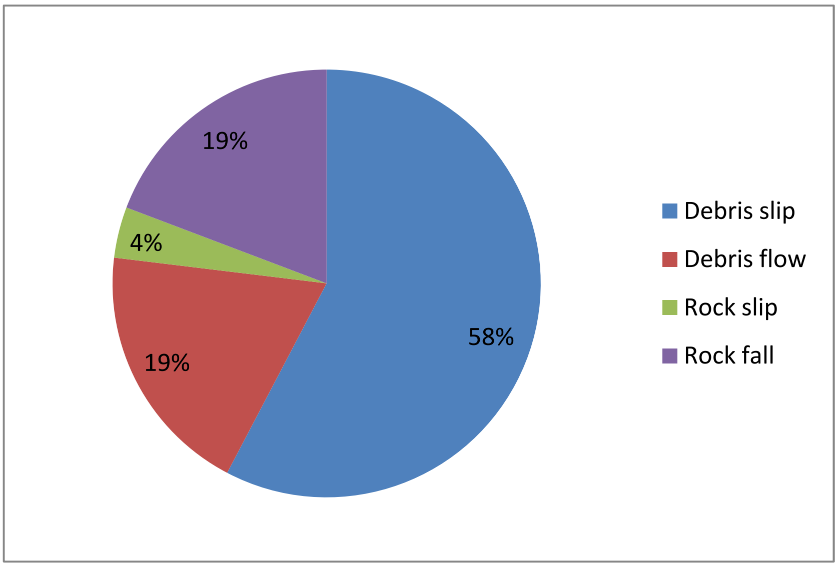



**Figure 6.6.** Landslide types in the study area.

**Table 6.3.** Damaging historic landslides in the study area.

| ID# | Date | Easting | Northing | Locality | Description | Type | Trigger | 24hr rain/mm | Volume | Damage | Deaths | Data source | Sub-source |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 26 | 2/23/1995 | 2417440 | 5956760 | Aldridge's Hill. SH67 | Slip | DS | R | 42 | -99 | Car damaged | 0 | Lowe. 2001 | WCRC Landslide Archive. |
| 44 | 6/27/2002 | 2414575 | 5952300 | Back Road. Granity | Slips | DS | R | 154 | 500 | 6 Houses evacuated | 0 | The Press | WCRC Landslide Archive. |
| 157 | 3/17/2007 | 2419870 | 5956010 | Charming creek walkway | Slip | DS | R | 88 | -99 | Walkway damaged | 0 | Westport News | WCRC Landslide Archive. |
| 192 | 2/23/1995 | 2417440 | 5956760 | Deans Creek. SH67 | Slip | DS | R | 42 | -99 | House Damaged | 0 | Lowe. 2001 | WCRC Landslide Archive. |
| 304 | 12/25/1949 | 2415012 | 5952095 | Granity | Rockfall caused by cloudburst | RF | R | -99 | -99 | Serious damage to houses | 0 | Benn. 1990. | WCRC Landslide Archive. |
| 305 | 10/17/1940 | 2417248 | 5952250 | Granity - Millerton rd | NO DESCRIPTION | DS | R | 102 | -99 | interputed traffic | 0 | Benn 1990 | Emily Smith |
| 359 | 7/1/1998 | 2415789 | 5955150 | Hector | Debris flow entered 6 houses | DFL | R | 118 | -99 | Houses damaged and road closed. 3rd time house damaged in 6 years. | 0 | Greymouth Evening Star 1-2/7/1998 | |
| 523 | 6/16/1929 | 2417105 | 5952382 | Millerton | Large slips caused widespread damage and killed 1 man | DS | EQ | -99 | -99 | Landslide dams. widespread damage. | 1 | Benn 1992 | |
| 524 | 6/6/1952 | 2416320 | 5951214 | Millerton Mine | Coal face collapse. injures Man | RS | A | -99 | 100 | 1 Man injured | 0 | Westport News | |

| ID# | Date | Easting | Northing | Locality | Description | Type | Trigger | 24hr rain/mm | Volume | Damage | Deaths | Data source | Sub-source |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 525 | 10/7/1930 | 2418133 | 5952151 | Millerton mine road | 6 slip | DS | R | 125 | -99 | mine operation halted | 0 | Benn 1990 | Emily Smith |
| 526 | 6/27/2002 | 2418133 | 5952151 | Millerton Road | Slips | DS | R | 154 | 200 | Road closure | 0 | The Press | WCRC Landslide Archive. |
| 530 | 7/23/2009 | 2417285 | 5953153 | Mine Creek. Stockton. | Debris flow of soils. rock and vegetation | DFL | R | 112 | -99 | Water quality problems | 0 | Glen Drummond. Solid energy Report | WCRC Landslide Archive. |
| 583 | 3/20/1935 | 2416845 | 5954324 | Ngakawau | debris flow. deposited material at least 6m deep. | DFL | R | -99 | -99 | cover road bridge to 6m & rail to 3.6m | 0 | Benn 1990 | Emily Smith |
| 584 | 2/14/1949 | 2417230 | 5955069 | Ngakawau | Collapse of tunnel entrance on trainline | RF | A | -99 | 1000 | Train line closed 1day | 0 | Westport News | |
| 585 | 3/1/1952 | 2417230 | 5955049 | Ngakawau | Slips | DS | R | 88 | 50 | Not reported | 0 | Westport News | |
| 586 | 4/29/1981 | 2416459 | 5954118 | Ngakawau | Slips | DS | R | 39 | -99 | Road closures | 0 | Benn. 1990. | WCRC Landslide Archive. |
| 587 | 4/29/1953 | 2419156 | 5958637 | Nikau | NO DESCRIPTION | DS | R | -99 | -99 | house damage. roads impassable | 0 | Benn 1990 | Emily Smith |
| 588 | 2/23/1995 | 2419722 | 5959459 | Nikau. SH67 | Slip | DS | R | 42 | -99 | Dwellings damaged | 0 | Lowe. 2001 | WCRC Landslide Archive. |
| 671 | Unknown | 2415200 | 5952363 | No Description | rock fall | RF | U | -99 | 10 | Not reported | 0 | Lamorna Cooper | |
| 738 | Unknown | 2415469 | 5952137 | No Description | rock fall | RF | U | -99 | 105 | Not reported | 0 | Lamorna Cooper | |

| ID# | Date | Easting | Northing | Locality | Description | Type | Trigger | 24hr rain/mm | Volume | Damage | Deaths | Data source | Sub-source |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 970 | 1/29/2007 | 2413634 | 5951021 | No Description | FLASH FLOOD BRIDGE 148 GRANITY. reported by NZ Police debris cleared by Ganger track clearance 1506 hours 80 minutes. | DFL | R | 68 | 50 | Not reported | 0 | OnTrack Incident Reporting | |
| 1714 | 10/27/1998 | 2414087 | 5950425 | SH67 Granity | Slips | DS | R | 50 | -99 | SH67 closed | 0 | Greymouth Evening Star 27-*28-29/10/1998 | |
| 1717 | 10/27/1998 | 2420821 | 5961965 | SH67 Nikau | Slips | DS | R | 50 | -99 | SH67 closed | 0 | Greymouth Evening Star 27-*28-29/10/1998 | |
| 1719 | 6/27/2002 | 2414087 | 5950625 | SH67. granity | Slips | DS | R | 154 | 200 | Road closure | 0 | The Press | WCRC Landslide Archive. |
| 1721 | 3/17/2007 | 2400013 | 5938945 | SH67. north of Westport | NO DESCRIPTION | DFL | R | 246 | -99 | SH67 closed | 0 | DMC Monthly Report | GNS |
| 1755 | 2/20/1952 | 2415775 | 5946768 | Stockton Mine | Machinery caused coal face collapse | RF | A | -99 | 150 | 1 Man injured | 0 | Westport News | |

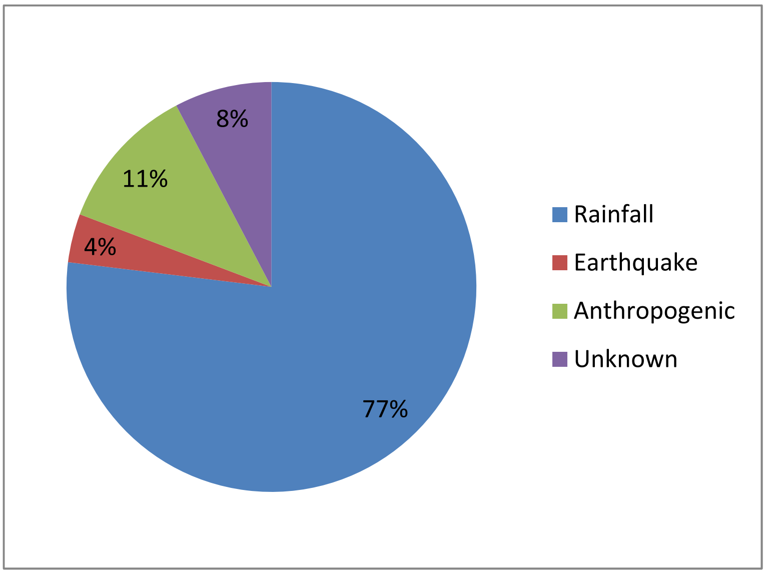



**Figure 6.7.** Pie chart showing the triggers of landslides in the study area.

Figure 6.7 shows that rainfall is responsible for triggering the vast majority of landslides in the study area, with 77% of the landslides attributed to rainfall. Interestingly, 11% of the slides are reported as anthropogenically triggered, which may be due to the method of reporting, where a landslide or rock fall which caused injury at a mine site will have a much greater chance of appearing in the local newspaper, than a landslide that occurred naturally. Earthquake-triggered landslides are the smallest category of reported landslides. This is due to the fact that only one earthquake event, the 1929 Murchison earthquake, triggered landslides during the reporting period in this study area, but that event was responsible for triggering many slides during the same event. This earthquake was responsible for triggering the landslide that caused the only death attributed to landsliding in the study area.

Figure 6.8 shows a plot of the 24hr rainfall associated with the rainfall generated landslides in the study area. From this it can be seen that as little as 50mm in 24hrs can trigger landslides. At rainfall amounts over 100mm in 24hrs, debris slips often transform into debris flows.

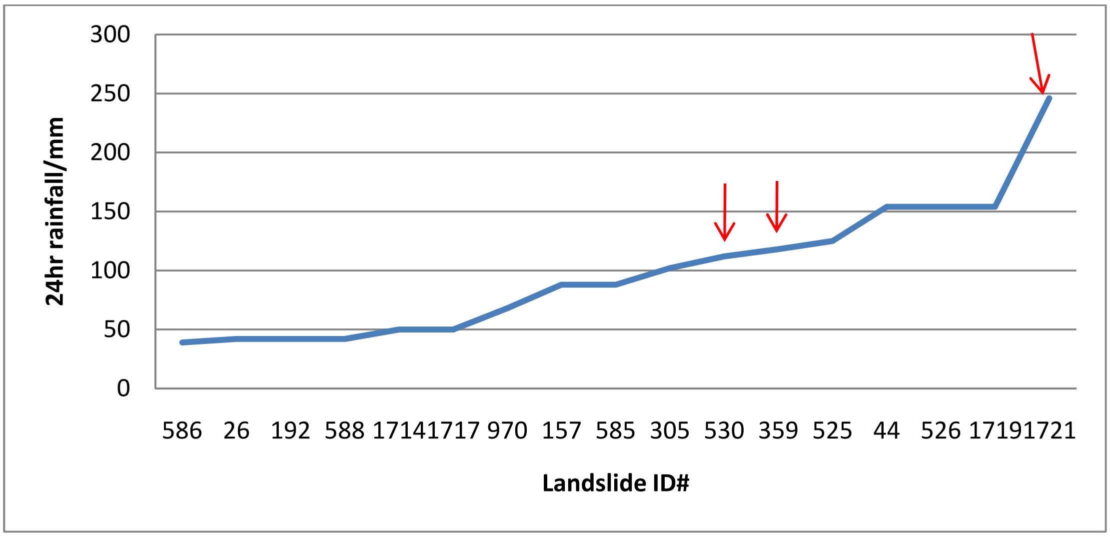



**Figure 6.8.** 24hr rainfall amounts in mm for the rainfall triggered landslides in the study area. Red arrows indicate debris flows.

The volume (size) of landslides in the study area varies considerably, but hundreds of cubic meters is not uncommon and as large as 1000 $m^3$ has been reported.

The previous, brief overview of past landslides in the area from Waimangaroa to Nikau is sufficient to show the general character of landsliding in the area. Since the reporting of landslide occurrences is sporadic through time, and no complete spatial/temporal inventory is available in the study area, no estimation of return periods or annual probability of occurrence can be made.

In summary, landsliding is a common problem in the area between Waimangaroa and Nikau. Debris slips are commonly triggered by rainfall amounts of as little as 50mm in 24 hours. These slips can transform into debris flows, which are a faster moving, further reaching landslide type. Property damage and disruption to the road and rail networks has frequently been reported

6.5.2.3 Comparison of asset information to the landslide susceptibility map

Figures 6.9, 6.10 and 6.11, 6.12 show the study area from north to south as displayed on the landslide susceptibility map. Using information obtained from the

Buller District Council, building footprint centroids were digitised and the buildings classified into their specific usage types. Only buildings located on the inland side of State Highway 67 were digitised as the entirety of the land on the seaward side of the road is classified as very low or low susceptibility to landsliding. Also displayed on these maps are the property parcel boundaries, proposed new subdivisions, landslide catalogue entries, outlines of the disturbed area of rainfall triggered landslides and the outline of the "rockfall and rapid debris flow hazard zone".

This section identifies the elements at risk and explains general observations of the landslide susceptibility map in comparison to the asset information held at Buller District Council.

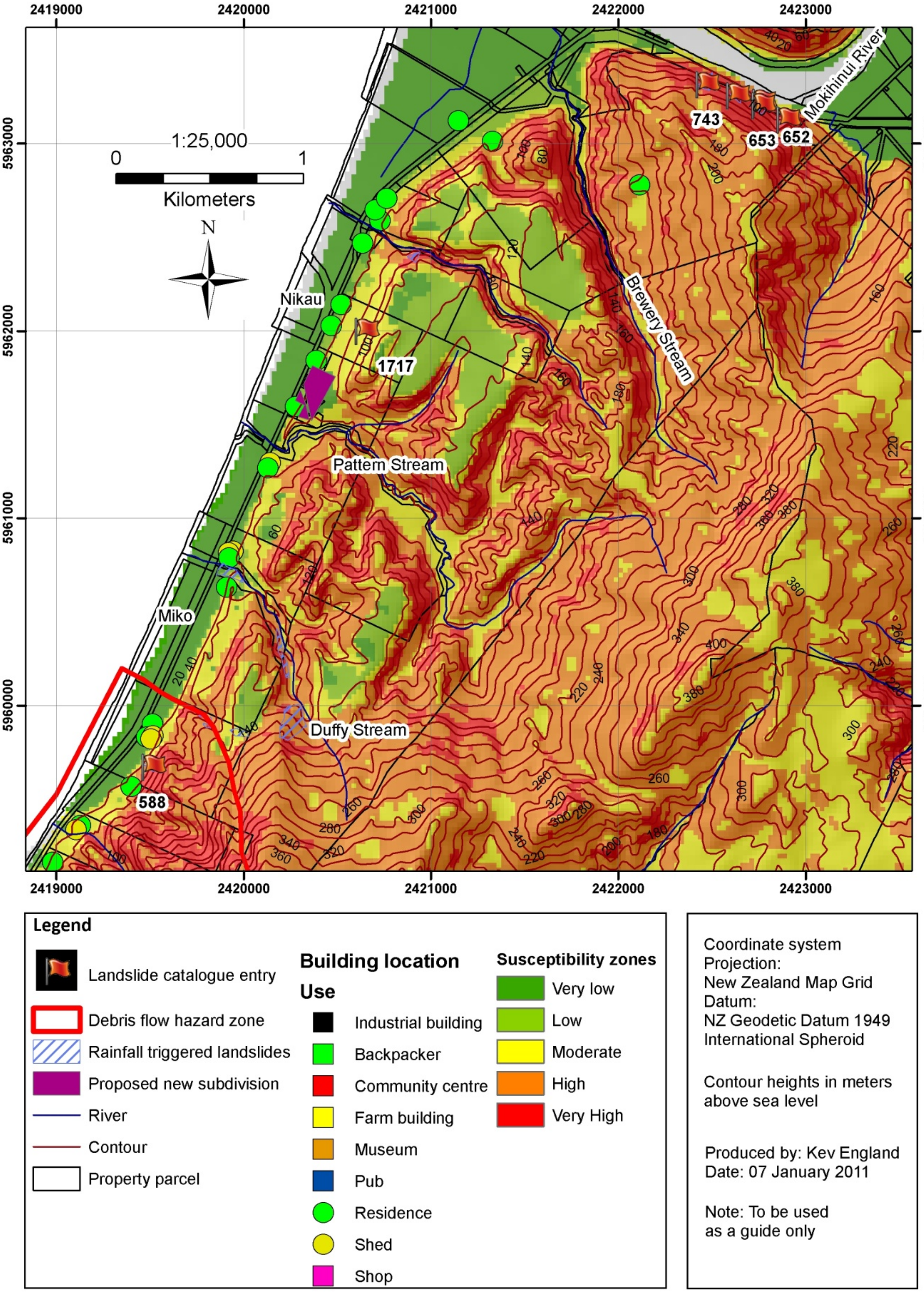



**Figure 6.9.** Landslide susceptibility map of the study area (northern section).

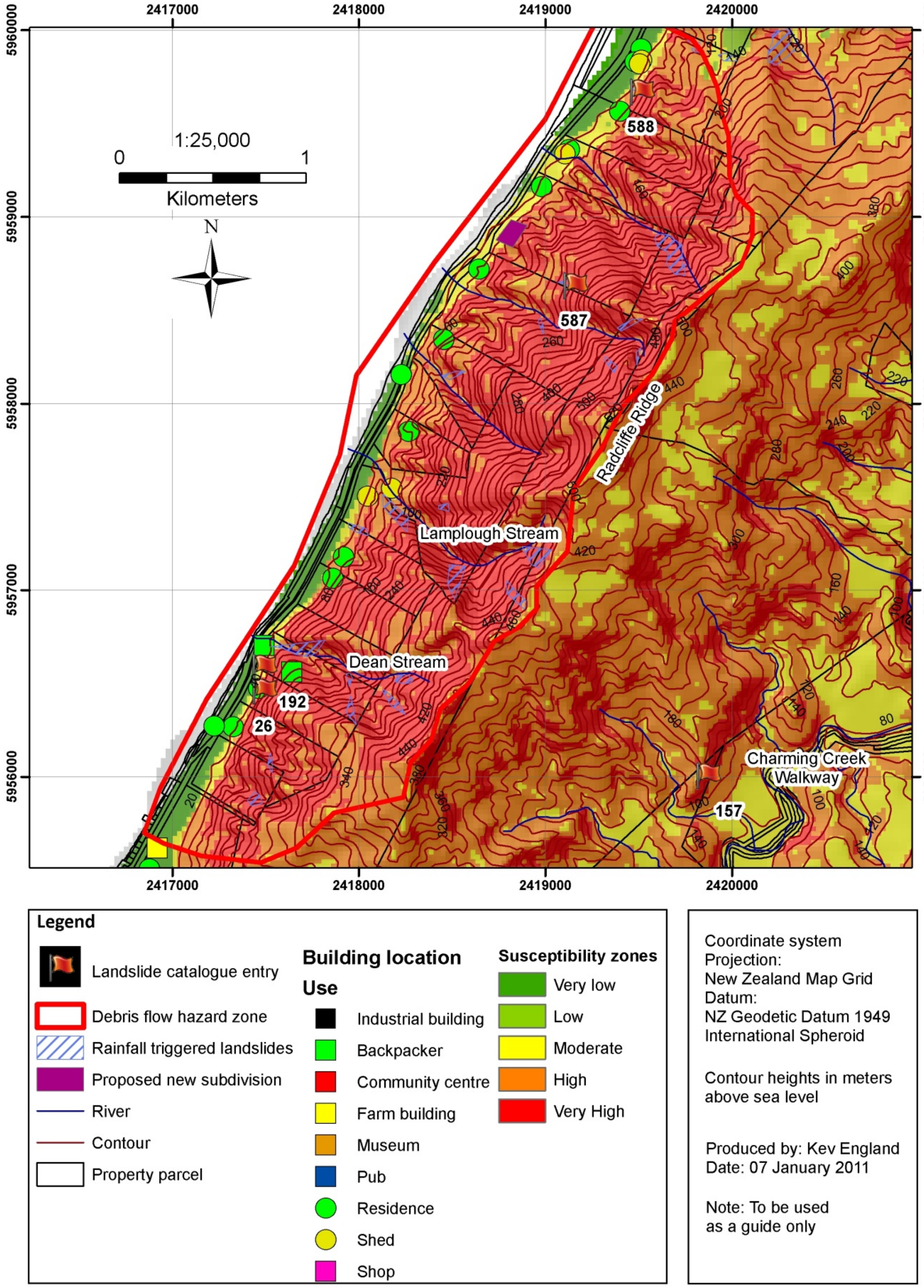



**Figure 6.10.** Landslide susceptibility map of the study area (north central section).

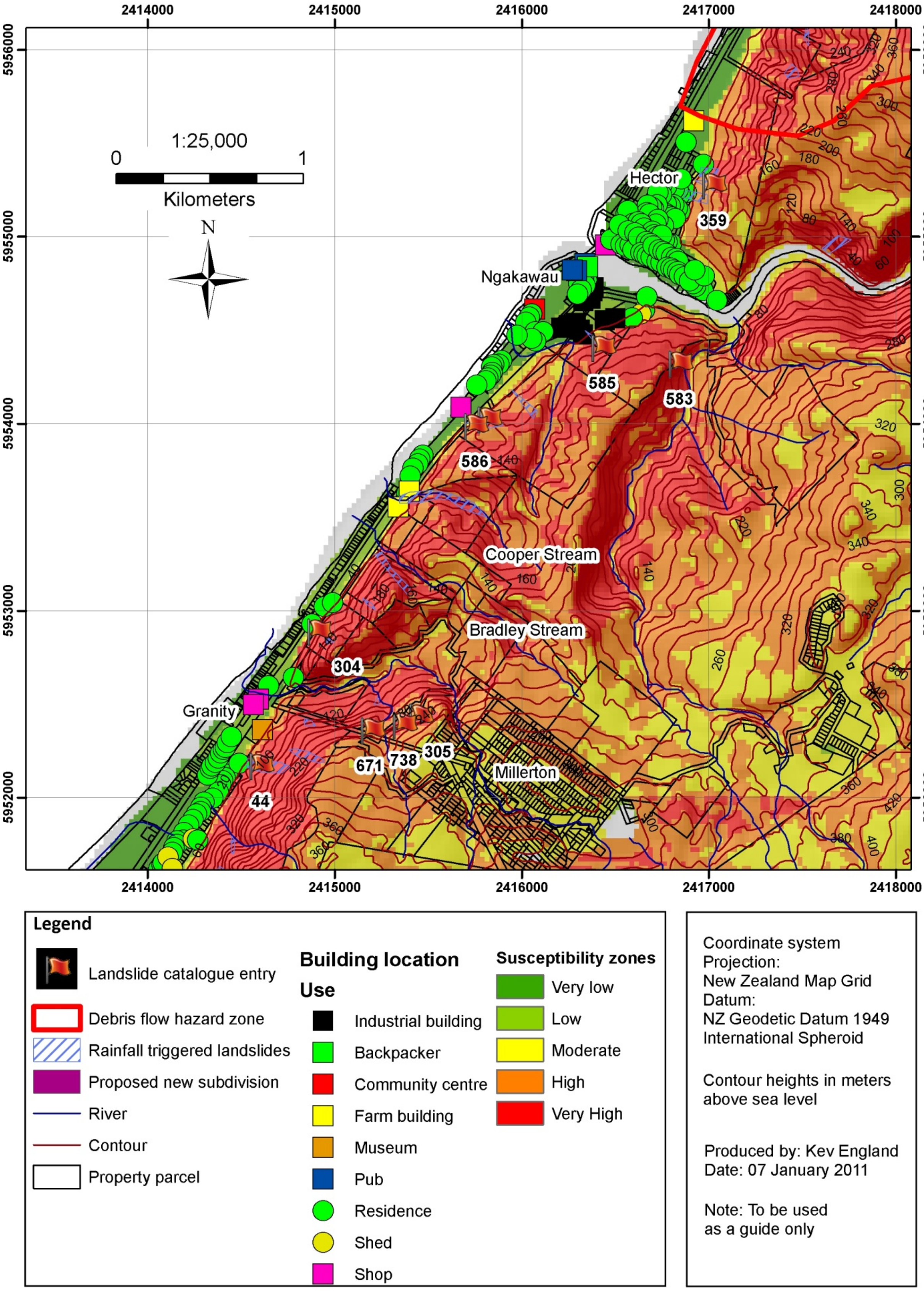



**Figure 6.11.** Landslide susceptibility map of the study area (south central section).

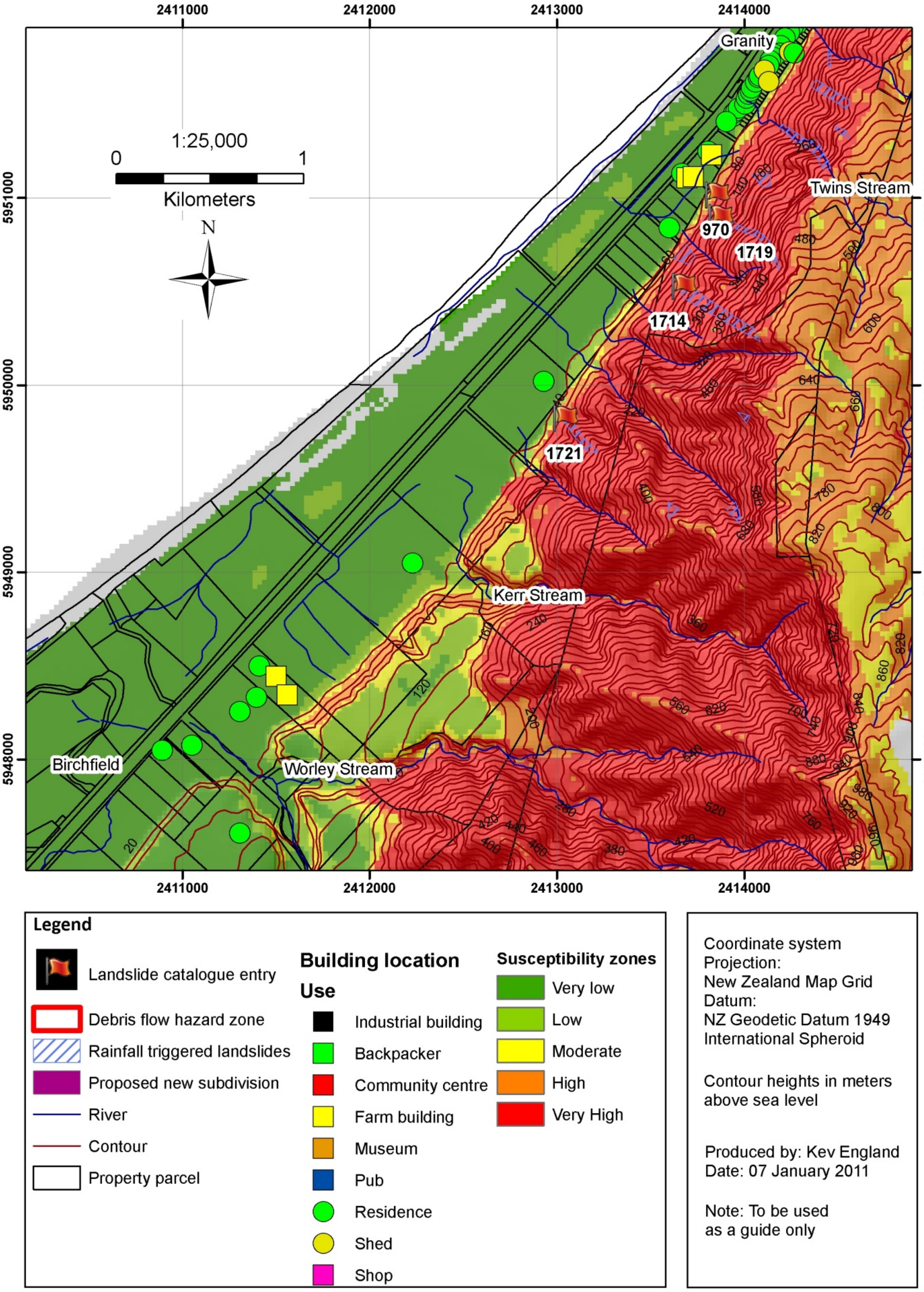



**Figure 6.12.** Landslide susceptibility map of the study area (southern section).

In general, the steep land below Radcliffe Ridge and the Millerton Plateau falls in the zone of very high susceptibility to landsliding. Visible landslides are very common and many have reached the base of the slope behind the towns of Granity, Ngakawau and Hector. For much of the study area, the distance between the base of the steep hillside below Radcliffe Ridge and the high tide point of the Tasman Sea is often as little as 150m.

The prediction of volume and run-out distance of landslides has not been attempted in this thesis as it is not possible to accurately define these variables on a regional scale. However, it is reasonable to assume that a larger slope is capable of producing a larger landslide and the corresponding landslide run-out distance will also be greater than for smaller slopes. In respect to landslide volumes and associated length of run-out distances in the study area, it can be expected that the slope beneath Radcliffe Ridge and the slope inland of Granity (from the Museum south) are likely to generate the largest landslides with the longest run-out distances.

Within the existing “rockfall and rapid debris flow hazard area”, there are 13 residences, (all BIC 2a or 2b) of which 2 are located in the zone of very high susceptibility, 2 are located in the zone of high susceptibility 5 are located in the zone of moderate susceptibility and the remaining 4 residences are located in the zone of very low susceptibility to landsliding. There are also 2 commercial buildings (BIC 2b), both currently operating as a backpacker’s hostel, one of which is located in the very low susceptibility zone and the other is well within the zone of very high susceptibility to landsliding. There are also a number of farm sheds and shelters (BIC 1), which are mostly situated in the lower susceptibility zones. In addition to these buildings there is one proposed new subdivision, which occupies land shown as moderate, high and very high susceptibility to landsliding.

To the north of the “rockfall and rapid debris flow area”, there are 14 residences (BIC 2a and 2b) of which 7 are located in the zone of very low susceptibility, 3 are in the zone of low susceptibility and 4 are in the zone of moderate susceptibility to landsliding. There are also a number of farm sheds (BIC 1) that occupy land in the lower susceptibility zones, and 1 proposed new subdivision, which occupies land in the very low and low susceptibility classes.

The town of Hector has many residences built on the flood plain gravels on the north bank of the Ngakawau River, all but one situated in the zone of very low susceptibility to landsliding. There is one property towards the north east of the town that is situated in the moderate zone. There are however, many properties situated very close to the steep hillside to the east of the town which is variably classified as moderate, high and very high susceptibility to landsliding. The outlines of past landslides show that landslides are a very real concern for the residents of houses closest to the hillside and the catalogue entry # 359 explains that repeated instances of property damage have occurred in the past.

The town of Ngakawau, on the south side of the Ngakawau River mouth, is in a very similar situation to the town of Hector, with the addition of some heavy industrial buildings which service the base of Stockton coal mine's aerial ropeway, where coal is stockpiled and loaded onto trains for transportation to Lyttelton. There are 2 residences to the east of the town that are situated in a zone of high susceptibility to landsliding, but most of the residences and businesses are located on flat ground, a reasonable distance from the steep hillside.

Between the towns of Ngakawau and Granity, close to Cooper Stream, there are two businesses and one residence, which are located in a zone of low susceptibility to landsliding, but within 40m of the very high susceptibility zone. Cooper Stream has experienced debris flows in the past and the outline of the disturbed area of this debris is within a few meters of the business and residential buildings. Slightly further south, about 400m south of Bradley Stream are 3 more residences which are positioned in a zone of medium susceptibility, but within 40m of the zone of very high susceptibility to landsliding. Mapped landslides can be seen on the hillside above these properties.

In the town of Granity itself there are numerous residences and a museum that are positioned very close to the base of the steep hillside, all of which fall within the zone of very high susceptibility to landsliding. Landslides are visible behind the town and damages have been caused by rockfalls and debris flows. On one occasion, as detailed in catalogue entry # 44, 6 houses were evacuated due to debris slips in close proximity to the houses.

South of Granity, the coastal plains are wider and have allowed building construction much further from the steep hillside. There are no residences or other buildings located in the higher susceptibility zones.

### 6.5.3 Discussion and recommendations

Historic residential developments in Granity, Ngakawau and Hector occupy a very narrow strip of coastal land between an eroding coastline and the steep range-front to the east of the towns. As a response to the threat of coastal erosion and the scarcity of suitable building sites in the towns many properties are located very close to, or directly adjacent to, the zone of very high susceptibility to landslides. The residences in closest proximity to the very high susceptibility zone are undoubtedly at high risk from landslide damages, especially in Granity, where the likelihood of large landslides is the highest. This development occurred before the landslide hazard was realised, which necessitates a risk-based approach to manage the landslide hazard.

For historic properties in Granity, Ngakawau and Hector that lie in or within 50m of the higher susceptibility zones, the most pressing concern is to educate the current residents about the landslide hazard. It should be understood by people delivering the hazard education that the end goal of this education program is disaster prevention. Given the low level of formal education and complex socio-economic nature of these communities, a careful approach on a case by case basis will be required. For example, it should not be assumed that all residents here can read. Fortunately, the number of properties that fall within this category is minimal, so a personal approach to landslide hazard education should be possible. In order to educate the whole community, mail-drop leaflets may be a suitable option. A more detailed landslide risk analysis should be carried out for the properties identified as highest risk, and the appropriate actions taken. Considering the low property prices and low incomes of the residents of the area, costly mitigative structures will most likely not be a feasible option. Incentives to retire the most at risk properties may be successful in persuading house owners to relocate to a more appropriate location, especially if these properties are close to the end of their useful life.

Visible landslide scars mark the hillside behind these towns and may serve as a reminder to residents of the landslide hazard. However, the opposite effect is also possible; the high frequency of small landslide events may have encouraged residents to accept the landslide risk. This acceptance may be a calculated compromise between lifestyle choices, economics and exposure to the landslide hazard, but equally, it may simply reflect the community's unawareness of their vulnerability to the landslide hazard.

This risk acceptance, be it calculated or not, has almost certainly played a role in promoting the development of "lifestyle" type properties on landslide-prone land in the area north of Hector. Residents of these properties should be educated about the landslide potential in this area. For properties that lie within the higher susceptibility zones and that were constructed prior to the 1996 designation of the "rockfall and rapid debris flow hazard zone" detailed risk analysis studies should be conducted and the appropriate actions taken. This may mean that mitigative structures are required, or relocation may be the preferred option.

Properties that were built after 1996 will have had a geotechnical engineer's report submitted with the building consent application. These reports are required to identify a safe building and effluent disposal site. The report is also required to assess the land in relation to a 100-year hazard including any mitigation measures. Since no detailed risk assessments have been completed on the frequency and magnitude of landslides in this area it is not possible to define a 100-year hazard. Therefore, the design criteria for any mitigation measures are also undefined and the recommendations put forward by the various geotechnical engineering companies may not have reduced the risk to the intended level. There are two solutions to this problem:

1. Either conduct detailed landslide risk analyses including magnitude/frequency relationships to define the building and subdivision consent requirements
2. Or rephrase the requirements for the geotechnical reports, so that they can be written with a higher degree of continuity.

The 1996 declaration of the “rockfall and rapid debris flow hazard area”, between Hector and Miko was a sensible, yet oversimplified means of addressing the landslide hazard issue. The lack of documentation that accompanies its inclusion in the District Plan has led to an unclear perception of its meaning. Also, the area occupied by Hector, Ngakawau and Granity has very similar terrain variables and landslide history to the “rockfall and rapid debris flow hazard area”, and is similarly zoned on the landslide susceptibility map. This discrepancy in hazard zoning has encouraged the residents of at-risk properties in Hector, Ngakawau and Granity to disregard the landslide hazard and consequently left them in a position of high vulnerability to landslide damage. Additionally, the absence of a landslide hazard zone in Hector, Ngakawau and Granity has devalued the meaning of the existing “rockfall and rapid debris flow hazard zone”, by allowing residents and potential land developers to ask the question: “why has one area been designated as hazardous, when another area with the same landslide hazard conditions and history not been classified as hazardous?”. To address this issue, the zones of the landslide susceptibility map should be used to define zones within the study area and appropriate rules applied to these zones.

This study delineates the landslide susceptibility based on the current ground and meteorological conditions. However, it is now widely accepted that the effects of climate change will cause increased frequency and intensity of adverse weather events, such as heavy rainfall (Smith and Petley, 2009). The affects of climate change over the next few decades can be expected to cause a corresponding increase in the frequency and magnitude of rainfall-triggered landslide events. Accurate prediction of these changes is not possible, but these effects must be considered when processing the application to build a property whose lifespan is expected to be at least 50 years. A program of monitoring these changes and updating the zone boundaries and rules relating to the zones accordingly may be beneficial. Table 6.4 summarises the most pressing issues and the suggested actions that should taken.

**Table 6.4.** Summary of landslide issues in the case study area and suggested actions.

| Issue | Suggested actions |
| --- | --- |
| Risk of direct impact or burial by landslide debris to historic residential developments in Granity, Ngakawau and Hector | Educate the inhabitants of the properties deemed to be most at risk on a case by case basis<br>Educate the remainder of the residents of the area by mail drop leaflets or a similar technique<br>Include the area south of the Granity museum in a "rockfall and rapid debris flow hazard zone" similar to the area between Hector and Mico.<br>Limit the existing use rights to rebuild in the most at risk locations<br>Conduct detailed risk analysis works for properties deemed to be most at risk. Relocate residents in the highest risk residences if the risk analysis suggests that this is necessary. |
| Risk of direct impact or burial by landslide debris or foundation collapse to newer "lifestyle" type developments in the higher susceptibility zones north of Hector | Ensure that current land owners are educated about the landslide risk.<br>Review the geotechnical engineer's reports and ensure that mitigative structures are suitable.<br>Ensure that any mitigative structures are properly maintained. |
| Subdivision of land parcels and new building consent applications within the higher susceptibility zones | Disallow any building or subdivision consent application within the very high susceptibility zone.<br>Ensure that appropriate geotechnical guidance is received prior to allowing residential development of land in the high susceptibility zone or directly down-slope from the higher susceptibility zones. |
| Unclear requirements for geotechnical advice, for example, the requirement to mitigate against a 100 year hazard | Either conduct detailed landslide risk analysis including magnitude/frequency relationships to define the requirements<br>Or, rephrase the requirements of the geotechnical reports, so that they can be written with a higher degree of continuity |
| Currently undefined landslide hazard zones | Adopt the landslide susceptibility map to define the zones of landslide hazard throughout the District and apply rules to these zones to promote continuity of landslide hazard management |

| Issue | Suggested actions |
|---|---|
| Increased frequency and magnitude of landslides in the area due to climate change | Monitor the effects of climate change on landslides in the area and adjust the zone boundaries and rules accordingly<br>Apply regulations that anticipate the increased magnitude and frequency of landslides |

The current *status quo* that exists within the area between Waimangaroa and Nikau in regards to landslide hazard management has left many of the residents of this area vulnerable to landslide hazards. This study helps to define the areas that are more or less likely to experience landslides and displays past landslides that have occurred in the area. This information can be used by Buller District Council to establish the location and extent of landslide hazard zones, and put clear definitions on the rules applied to each zone. Once this is achieved, an appropriate landslide hazards education program should be designed and delivered to the effected residents. Monitoring of the uptake of this information will be essential to ensure that the desired results are achieved.

# Chapter 7. Discussion

## 7.1 Introduction

This chapter identifies and discusses the key findings of the thesis and critically appraises the modelling techniques, testing and validation techniques, input data and the effectiveness of the landslide susceptibility map and landslide catalogue. It also discusses the usefulness of these landslide hazard management tools with respect to the eventual goal of landslide damage reduction. The limitations of the work are discussed and key areas for further research are suggested.

In chapter 5 it was shown how the correlations between terrain variable classes and the landslide distribution were established. It also explained how the quality (i.e., reliability and predictive power) of the susceptibility maps was quantitatively assessed by means of the success rate testing. These evaluation procedures firstly established the “goodness of fit” of the thematic data and the statistical methodology, by testing the success rate of the susceptibility maps against the landslide inventory distribution that was used to generate the maps. After this, it was shown how the “predictive power” of the susceptibility maps was assessed using a new set of aerial photography. The differences between these two testing procedures and the implications of the results are discussed in this chapter.

The landslide catalogue has been used in this study to display past landslides and aid in the decision-making process when considering land use changes or dealing with existing landslide hazard issues. A detailed analysis of the data has not been performed, but an explanation of its usefulness and limitations is presented in this chapter.

Chapter 6 explains the use of the landslide susceptibility map and landslide catalogue in landslide hazard management from a Council planning perspective. The present chapter highlights the key observations and discusses the successes and limitations of this approach.

This chapter will discuss:

1. The significance of the total weights *($W_i$)* calculated for the various classes within each factor map

2. The results of the success rate testing and validation procedures
3. The choice of modelling and validation techniques used in this study, in comparison to other techniques used to assess landslide susceptibility
4. The usefulness and limitations of the landslide catalogue
5. Limitations of the research
6. The effectiveness of these tools for landslide hazard management in the West Coast region
7. Scope for further study

## 7.2 The significance of the total weights *($W_i$)* calculated for the various classes within each factor map

One of the primary objectives of this thesis was to establish the correlation between landslides and the terrain variables that control them. The weights of evidence method (Bonham-Carter, 1994) achieves this by assigning weights to factor classes based on the presence or absence of landslides in that class in comparison with the presence or absence of landslides in the other classes. A positive weight indicates that the class is relatively favourable for the occurrence of landslides and a negative weight indicates that it is not. Further to this, weights with a wide range of values for classes in the same factor map indicate that that factor is useful in the prediction of landslides (Van Westen *et al.,* 2003). It follows from this that weights close to zero have little relation to the occurrence of landslides.

Figure 7.1 shows the range in calculated weights for the 8 factor maps chosen for the landslide susceptibility analysis. From this it can be observed that land cover is the most important variable in the control of landslides in the West Coast region, with an especially strong correlation in the Western area. This is certainly a useful observation, but may be an indirect effect of other factors that are related to the land cover class. For example, the land cover class that shows the lowest total weight ($W_i$) is freshwater and saline vegetation, which will most likely occupy land in the valley floor or within the tidal zone, so will necessarily be at very low slope angles and usually lies on quaternary unconsolidated sediments. So, the total weight ($W_i$) for areas occupied by freshwater or saline vegetation most likely reflects other associated factors such as slope and geology, not simply the land cover factors. However, regardless of the indirect associations between the factor maps, the land cover factor map is very useful in the prediction of landslides.

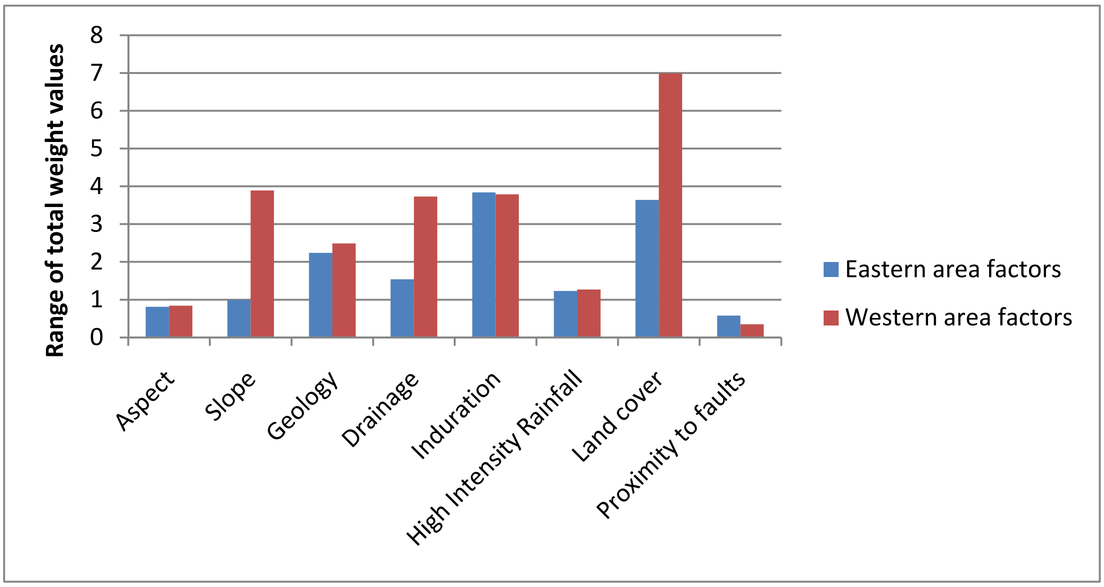



**Figure 7.1.** Range in calculated weights for the 8 factor maps.

The role of slope in the control of landslides has strongly divergent results from the western area to the eastern area. In the western area slope appears to be the second most influential factor and in the eastern area slope is the second least influential factor. Since slope is widely regarded as the principal controlling variable in the occurrence of landslides (Dai and Lee, 2002; Korup, 2005) these results deserve to be discussed.

The result for the western area, with a range of total weights ($W_i$) of close to 4 is an expected result and shows that slope is a highly influential factor in the occurrence of landslides. In contrast to this, the range of total weights ($W_i$) for the eastern area is 1, which suggests a much weaker influence on the landslide distribution. This may be partly due to introduced error from the original landslide inventory layer, as the availability of aerial photography for this area is very limited. Also, the mapping techniques used to produce the landslide inventory layer precluded the possibility of differentiating between source and deposit areas of a landslide scar. This means that a landslide that was initiated in steep terrain and travelled down-slope, later depositing material in the valley floor will cover pixels of the slope map that represent slopes of all angles. This is true of landslides that have occurred in both areas (east and west of the Alpine fault), but since the area of very low slope is much smaller in the eastern area (Southern Alps) than the western area the effect is much more noticeable.

Figure 7.2 shows the total area occupied by each slope class and the total area of landslides in each slope class. It can be seen from this, that the area of very low slope angle (0-10˚) is an order of magnitude larger in the Western area (5675km$^2$) than the eastern area (613km$^2$), yet the landslide areas in this slope class are much more similar between the eastern (1 km$^2$) and western (3km$^2$) areas. The effect of this is that the total weight ($W_i$) calculated for the 0-10˚ class in the eastern area will be artificially high due to the inability to differentiate between source and deposit areas of a landslide scar.

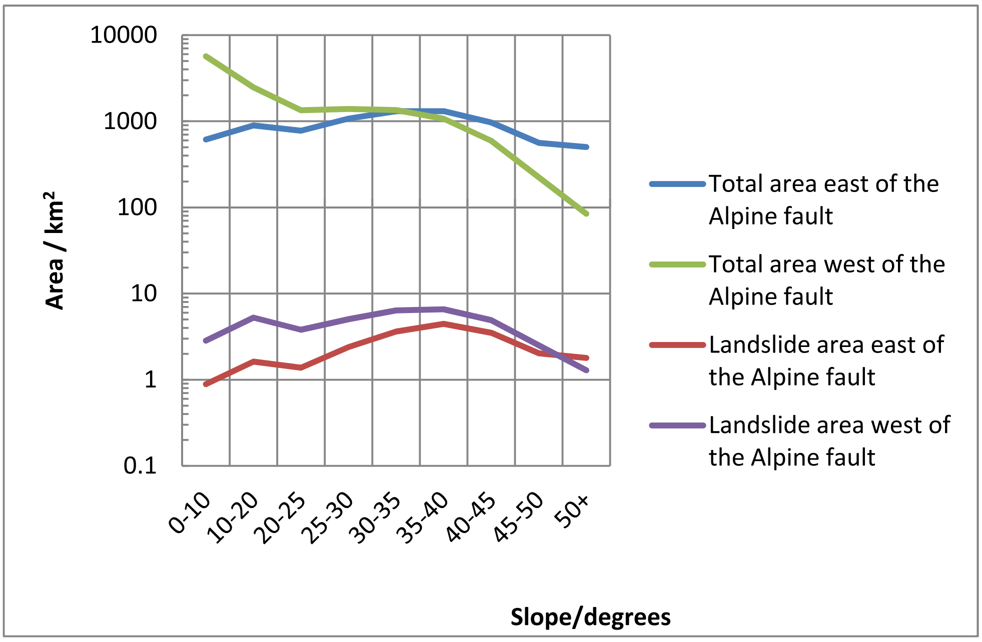



**Figure 7.2.** Total areas of the region and landslide areas (east and west of the Alpine fault) occupied by the different slope classes.

Further examination of figure 7.2 reveals that the total area east of the Alpine fault occupied by the different slope classes is closely mirrored by the areal distribution of landslides in the different slope classes for the eastern area. This indicates that the landslide distribution is relatively uniform in comparison to the slope classes and slope may not be a strong indicator in the control of landslides in the eastern area.

This variation in levels of influence from the eastern area to the western area (for the same terrain variable) illustrates the complex nature of the system being modelled and exemplifies the need to analyse additional terrain variables that may have a controlling effect on the spatial distribution of landslides. The relationships and interdependencies between the classes of the different factor maps are not explored in the weights of evidence method and the assumption is made that the factors are conditionally independent of each other. This oversimplification of a complex problem has been addressed by applying the AHP which effectively ranks the importance of the various factor maps.

One of the advantages of the statistical analysis approach to landslide susceptibility modelling is that it removes the subjectivity of expert based assessments (Dai *et al.,* 2002). However, it is clear that a measure of expert judgement is required to conduct a statistical study of landslide susceptibility and the application of the AHP relies largely on expert opinion. The superior success of the AHP method illustrates that a purely statistical approach can be improved by the application of rigorously applied techniques to address the issues of complexity within a system that can not be entirely represented by bivariate statistics alone.

## 7.3 The results of the success rate testing and validation procedures

Many of the previously published papers (e.g. Cevik and Topal, 2003; Dai and Lee, 2002; Suzen and Doyuran, 2003) that present landslide susceptibility assessments have discussed the results of a statistical analysis including the input data and the method used to prepare the model, but have avoided analysing the quality of the proposed model (Guzzetti *et al.,* 2006). This lack of validation significantly limits the usefulness of these studies. As noted by Chung and Fabbri (2003), without a proper validation no interpretation is possible; no support of the method or of the input data can be provided. The confirmation (or otherwise) of the validity of the model is not only necessary to prove its predictive accuracy, but also to help to communicate the significance of the predictions to the end users of the model outputs. This confirmation should explain the level of confidence to apply to the model and the output maps. This enables decision makers to use the model to promote safer land use with respect to the landslide hazard.

This study has utilised two techniques to assess the quality of the statistical models. Firstly, the success rate curve method of Chung and Fabbri (1999) was used to test the degree of match between the calculated landslide susceptibility index (LSI) scores and the landslide distribution that was used to generate the model. Secondly, the predictive accuracy of the models was tested by utilising the same procedure, but comparing the LSI scores to a landslide inventory derived from a new set of aerial photographs that was not used to generate the model. Remondo *et al.,* (2003) proposed that three strategies exist to obtain this independent landslide inventory dataset:

1. Landslides in the study area are randomly split into two groups, one for analysis and one for validation.

2. The study area is split in two allowing one area to be used for analysis and one for validation.
3. The analysis is carried out using landslides that occurred in a certain time period, and the validation is performed using landslides that occurred in a different (later) time period.

The last of these is obviously the most suitable to test the validity of the predictive maps, but the poor availability of aerial photography in the West Coast region meant that this was not possible. During the data collection phase of this study, every effort was made to find as much aerial photography coverage as possible, with the aim of mapping as many landslide scars as possible, thus providing a landslide inventory that was as complete as the data availability allowed. The aerial photography that was used for the validation was obtained, partly by chance, from the Animal Health Board, and conveniently satisfies the second of these strategies.

### 7.3.1 Success rate testing and sensitivity analysis

The results of the success rate testing show that the application of the analytical hierarchy process (AHP) improves the accuracy of the model output when compared to the results gained by using the weighting factor method (WFM) alone. The degree of model fit is established by this procedure and it was shown that the model for the western area predicted 20% of all landslides in the top 10% of the susceptibility scores and 40% of landslides in the top 20% of the susceptibility scores. The degree of fit for the eastern area was similarly accurate in the first part of the curve, with 20% of the landslides being predicted in the top 10% of the susceptibility scores, but accuracy declined in the lower susceptibility areas (40% of landslides were predicted by the top 26% of the susceptibility scores).

These figures support the validity of the model, in terms of goodness of fit of the data, and are comparable to other regional scale landslide susceptibility studies (Sarkar *et al.,* 2008; Dahal *et al.,* 2008). This proves the statistical significance of the model, but additional analysis is required to investigate the sensitivity of the model to changes in input data (Guzzetti *et al.,* 2006).

Since all thematic data layers have complete coverage of the study area, the assumption is made that the data contained in these layers is uniformly accurate throughout the region. However, this is not true of the landslide inventory layer, which was constructed by means of API wherever possible (high quality input data), and elsewhere, by means of mapping from satellite imagery, oblique aerial photography, observations from the ground and a limited amount of field mapping (lower quality input data). This allows the landslide inventory to be divided into two sets for comparative success rate testing:

1. Landslides mapped by aerial photography.
2. Landslides mapped by other means

Figures 7.3 (western area) and 7.4 (eastern area) show the comparison of the success rates for the areas of the region where aerial photography was used to construct the landslide inventory and areas where aerial photography was not available. The variation between the two success rates illustrates the sensitivity of the model to variation in input data.

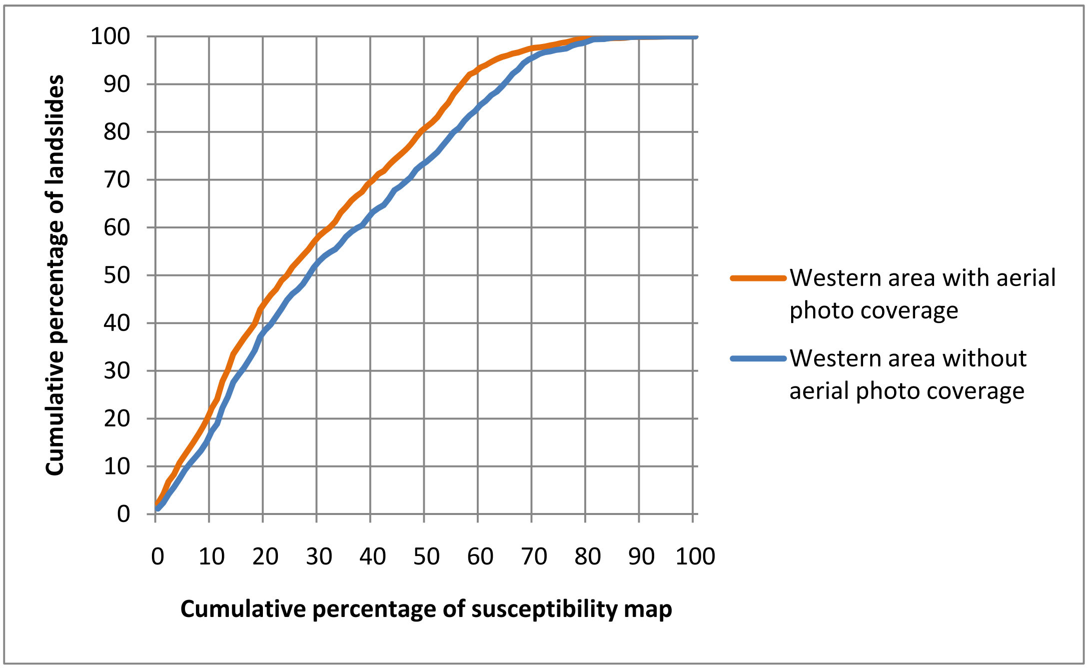



**Figure 7.3.** Comparison of success rates between areas with aerial photography coverage and areas with no aerial photography coverage (western area).

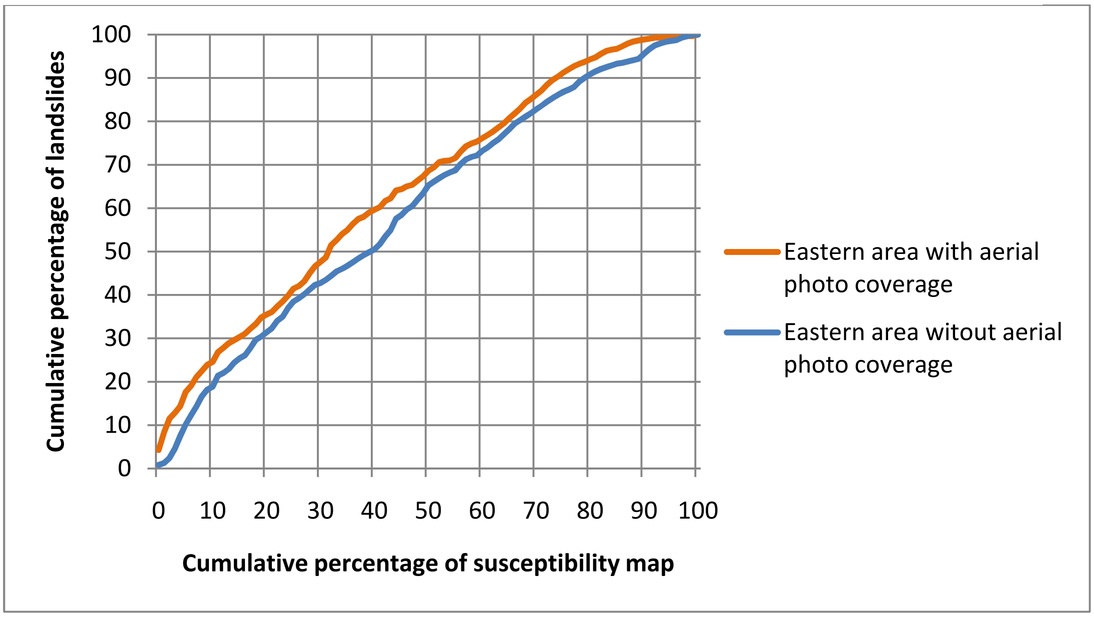



**Figure 7.4.** Comparison of success rates between areas with aerial photography coverage and areas with no aerial photography coverage (eastern area).

As expected, the areas with aerial photography coverage produced better fitting results in both the eastern and western areas. The degree of difference between the success rates for areas with aerial photography coverage and the areas without is not insignificant, but given the difference in the quality of the input data, the model produces surprisingly good results, indicating that it is a statistically robust model.

When comparing the degree of model fit between the models produced for the eastern and western areas it is clear that the western area is more accurate, with the lowest 20% of the susceptibility scores being landslide free. Even in the lowest percentiles of susceptibility scores for the eastern area landslides have occurred. This inaccuracy may be partly due to the limited availability of aerial photography in the eastern area, but may also be a true representation of the landslide susceptibility characteristics of this area. Figure 7.2 shows that the area occupied by steep terrain is much more widespread in the eastern area than the western area and consequently, the landslide distribution should be more widespread in the eastern area than the western area.

### 7.3.2 Validation

The independent landslide inventory dataset was used to conduct a validation of the models for each area, which gives a quantitative measure of the predictive power of the landslide susceptibility maps. In the case of the western map, 40% of the landslides occurred in 20% of the map with the highest susceptibility scores and 80% of the landslides occurred in 40% of the map with the highest susceptibility scores. In the case of the eastern map, the predictive power is lower (in comparison to the western map), with 30% of the landslides occurring in 20% of the map with the highest susceptibility values and 60% of the landslides occurring in 40% of the map with the highest susceptibility scores.

This difference in predictive power suggests that more confidence should be applied to the map area to the west of the Alpine fault than that east of the Alpine fault when making landslide hazard management decisions. Also, it was shown in figures 7.3 and 7.4 that the areas that have aerial photography coverage produced better results, so these areas should similarly be treated with greater confidence than the areas without aerial photography coverage. Figure 7.5 is a confidence map of the region, which illustrates the comparative levels of confidence that can be applied to the susceptibility map based on the validation and success rate testing results.

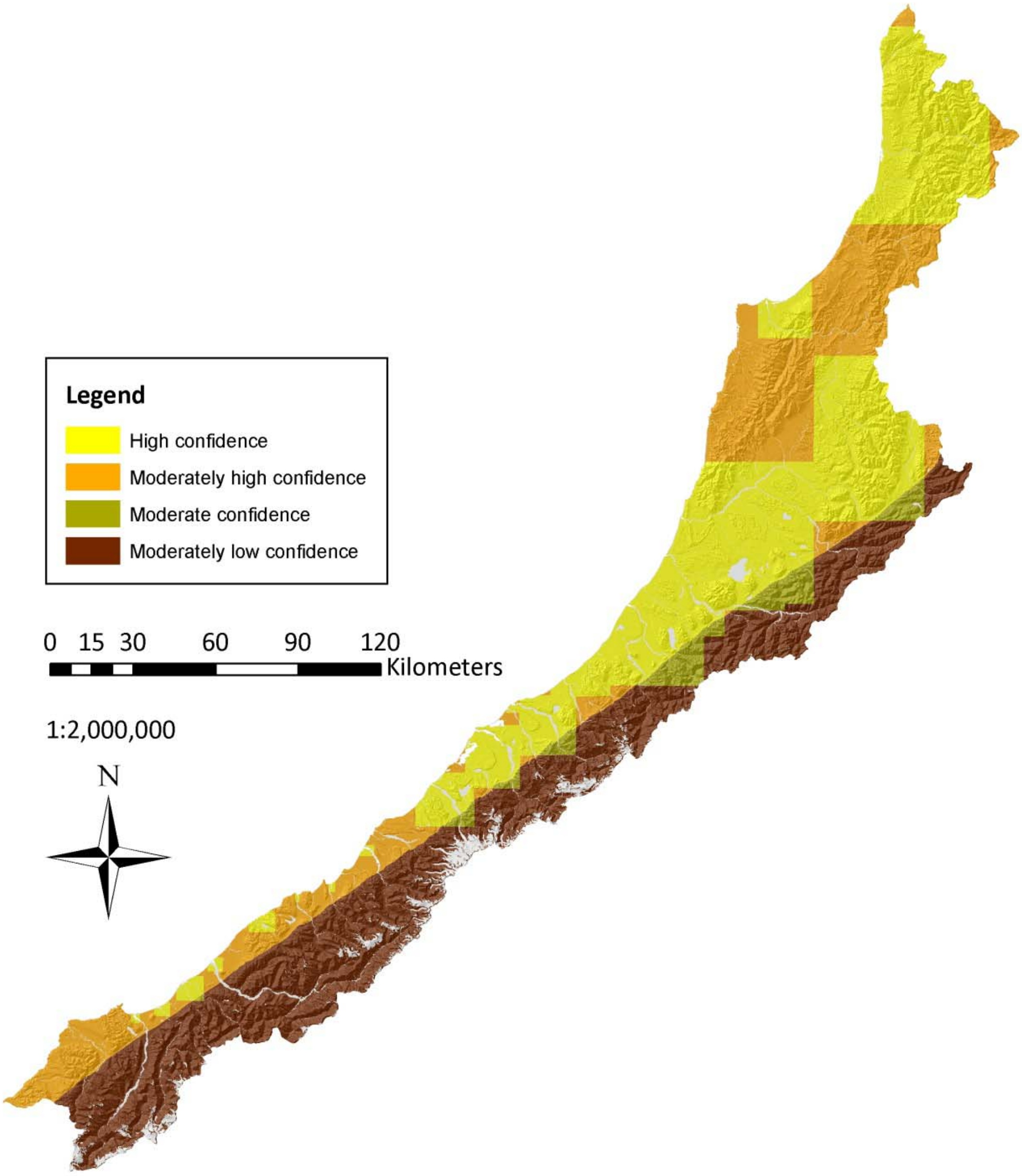



**Figure 7.5.** Confidence map showing the levels of confidence that should be applied to the information displayed on the susceptibility map.

It must be noted here that the availability of aerial photography for the validation procedure is very limited, with only 5.3% of the eastern part of the study area and 9.7% of the western part of the study area covered by this independent dataset. This means that the validation area may not be entirely representative of the whole study area. However, the random nature of the choice of area did provide an objective dataset to test the model against.

Since this validation was performed using an independent landslide inventory it can be expected that the model will predict future landslides to this same accuracy.

## 7.4 The choice of modelling and validation techniques used in this study, in comparison to other techniques used to assess landslide susceptibility

Most of the approaches used in mapping landslide susceptibility involve the accurate evaluation of a range of environmental factors acting as control variables in the occurrence of landslides. This involves the handling, interpretation and graphical representation of a large amount of spatial data (Magliulo *et al.,* 2009). GIS is therefore the most appropriate tool to use for landslide susceptibility assessments. GIS approaches usually involve the assigning of numerical weighting values to the different classes of the considered environmental factors. These approaches can be broadly divided into:

1. Direct (heuristic) methods involving expert evaluation of landslide predisposing factors. This relies entirely on the skills and experience of the observer, who applies a weight to geomorphological units based on the evidence of past landslides (such as scarps, debris, tilted trees, etc.) or the presence of other factors that might cause slope instability (such as rock fracturing, sub-glacial tills, water stagnation, etc.).
2. Indirect methods involving a statistical analysis of a landslide inventory in comparison to a range of classes of environmental factors. This is usually achieved by means of bivariate or multivariate statistics. These indirect methods remove much of the subjectivity of expert based evaluations, and are capable of producing quantitative results.

The direct methods require expert observations of the study area and are therefore limited to smaller geographic areas. In addition, the results are qualitative only, and usually divide the area into 2 or 3 susceptibility classes (Van Westen *et al.,* 2003). This limits the usefulness of the output susceptibility maps, but in areas where sufficient digital terrain data are not available this may be the only possible option.

Of the direct methods, bivariate statistics is a relatively easy method of preparing a landslide susceptibility map. However, the ease of analysis is achieved by assuming that all the factors are conditionally independent of each other. This has been recognised as an oversimplification, and is dealt with in this study by applying the AHP to derive values to rank the importance of the landslide predisposing factors. The results of the success rate testing and validation procedures prove that the use of the AHP has successfully addressed the issue of assuming conditional independence of the landslide predisposing factors. However, this adds an element of expert opinion to an otherwise objective study.

Multivariate statistical techniques do not assume conditional independence of the factor maps and usually involve the comparison of all classes of all factor maps to all the other classes of all the factor maps. The most commonly used multivariate techniques are linear and logistic regression, and discriminant analysis, which produce purely objective results (Clerici *et al.,* 2002). These techniques are formally more rigorous, but require a much deeper knowledge of mathematics, statistics and software (Magliulo *et al.,* 2009). Consequently, these techniques produce maps which are hard to comprehend and assess for non-specialists in statistics, such as local government planners and policy-makers (Clerici *et al.,* 2002).

A comparison of bivariate and multivariate techniques conducted by Suzen and Doyuran (2003) found that the two techniques produced maps which converge in approximately 80% of the study area. Considering the relative ease of conducting a bivariate statistical analysis and the similarity of the results the bivariate techniques are more suitable for a study such as this.

The validation technique is dictated in part by the choice of analysis technique, and the success rate method of Chung and Fabbri (1999) has been shown by many authors to be an appropriate technique to assess the model's "goodness of fit" of the data and of the predictive power of the output map (Guzzetti *et al.,* 2006; Dai and Lee, 2002; Gullà *et al., 2008;* Neuhäuser and Terhorst, 2007; Nandi and Shakoor, 2009; Thiery *et al.,* 2007; Cevic and Topal, 2003, Suzen and Doyuran, 2004).

The possibility exists for a validation of the zones of a landslide susceptibility map to be performed based on the locations of insurance claims relating to landslide damages. This would provide a measure of the number of landslides that have caused damage to properties within each susceptibility zone, and would therefore be extremely useful in communicating the landslide hazard information to local government planners and policy-makers. Unfortunately, the required data were not available, so this was not possible.

## 7.5 The usefulness of the landslide catalogue

As explained in chapter 3, the landslide catalogue details 1987 historic landslides throughout the West Coast Region. These were compiled from all the available data sources and stored in a format that can easily be displayed spatially in a GIS, or as a spreadsheet or database. The landslide archive held and maintained at WCRC, which provided the bulk of the catalogue entries, was stored as a Microsoft Word file, sorted by date, with only descriptive names for locations. This limited its usefulness as a tool for landslide hazard management, but did prove to be a useful reference document if combined with a high degree of local knowledge.

The primary goal of the landslide catalogue is to provide a tool that can be used to quickly and easily display the relevant landslide information for use in landslide hazard management by planners and consents staff at the Regional and District Councils. Chapter 6 illustrates the success of this aspect of the landslide catalogue for specific geographic areas within the Region. It provides non-technical people with an easy means of accessing historic landslide information that relate to their specific area of interest within the West Coast region.

A thorough analysis of the landslide catalogue has not been completed in this study. Figure 7.6 shows that the number of landslides reported per decade has been increasing since records began at the beginning of the last century. There is evidence that annual rainfall is increasing (Smith and Petley, 2009) so it is logical to assume that the frequency of rainfall triggered landslides should also increase. However, figure 7.6 shows that reporting of landslides has become more effective over time and does not show that landsliding has become more frequent. As a result of this it is not possible to use this catalogue for the calculation of magnitude–frequency relationships. However further analysis of the catalogue may provide useful results to aid in classifying landslide characteristics in the region.

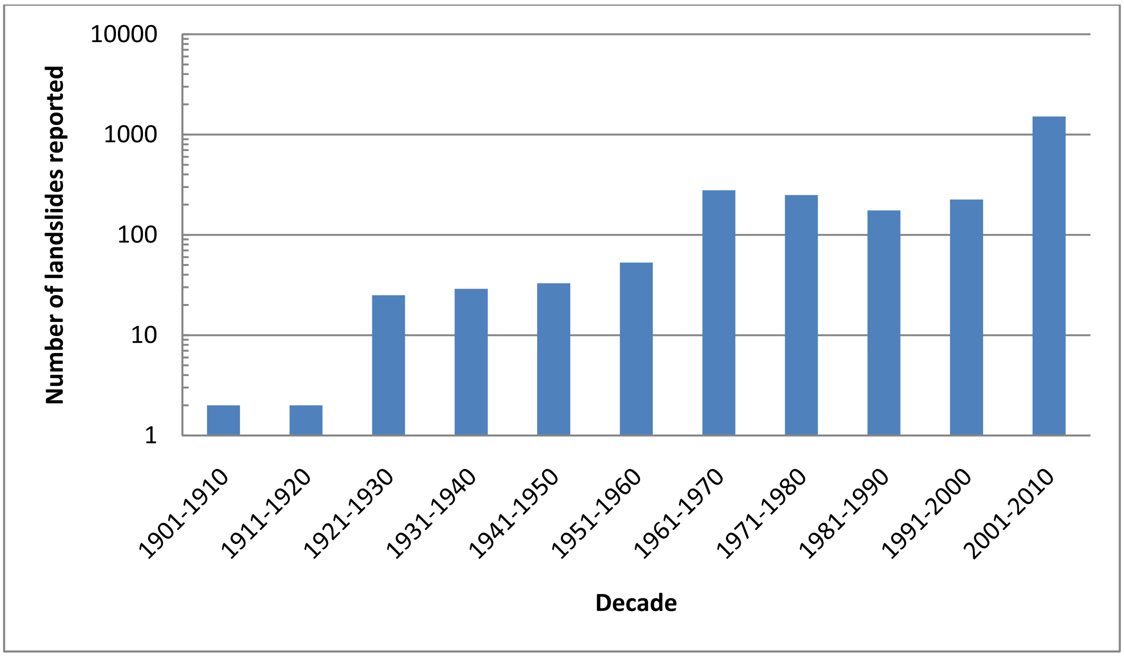



**Figure 7.6.** Number of landslides reported in the catalogue per decade.

If this catalogue is updated and maintained diligently by WCRC, its usefulness will increase over time. For example, the effects of climate change on landslide frequency and distribution may become evident.

## 7.6 Limitations

By definition, a landslide susceptibility map does not define the temporal characteristics of the occurrence of landslides (Fell *et al.*, 2008). Since timeframe is an essential part of the risk equation, a susceptibility map should not be used for detailed risk assessments.

This is a regional scale study and should be used as such. The scale used for the initial landslide mapping was 1:25,000 so the susceptibility maps should be viewed at that scale. The minimum mapping unit in this study is the 25m x 25m pixel, so this mapping precision should also be taken into account when using the susceptibility map.

This study models the landscape's susceptibility to rainfall-triggered landslides. It does not delineate the areas that are more or less likely to experience land instability issues during an earthquake.

Any landslide susceptibility study has a certain level of uncertainty (Guzetti *et al.*, 2006). Sources of uncertainty include:

- Errors and incompleteness in the landslide inventory
- Errors in the thematic factor maps
- Limitations in the technique chosen for the susceptibility analysis
- The inherent natural variability of the landslide phenomena

With regard to the sources of uncertainty, the introduced error derived from an incomplete landslide inventory is certainly an area of concern for this (and any landslide susceptibility) study. Due to the partial coverage of aerial photography for the region, the landslide inventory is incomplete. This will be true of all landslide susceptibility models, and must be taken into account when using the final map. The thematic factor maps are the best available, but due to scale and mapping roughness there may be errors introduced to the model from these sources.

Since the correlations between the landslide distribution and the terrain variables (and the eventual accuracy of the landslide susceptibility map) were improved by dividing the study area into the two sub-areas (east and west of the Alpine fault), it follows that the further subdivision of the study area may improve the results further. This observation implies that the smaller the study area, the greater the accuracy of the results. However, this study has assessed landslide susceptibility on a regional scale, and the accuracy of the results is correspondingly limited.

This model has an accuracy that predicts 80% of the landslides in the top 40% of the susceptibility scores. However, the model cannot claim to accurately delineate the probability of occurrence in each of the susceptibility zones. As with any natural process, landslides do not occur with a regularity that enables complete prediction of their behaviour. This model should be used with this in mind.

The landslide catalogue relies on reporting of incidents, so will be incomplete to varying degrees depending on the research efforts of the people who compile and maintain it. Also, the reporting of landslide occurrences will often be carried out by people who are untrained in the observation of landslides, or who are reporting them for purposes other than landslide hazard management. For example, many of the landslides included in the landslide catalogue were taken from newspaper articles. These entries often do not contain volumes, landslide type, or other pertinent information. Similarly, a roading contractor who reports on a landslide may give a reasonable estimate of the volume and type of material, but almost certainly will not give an accurate description of the type of failure.

## 7.7 The effectiveness of these tools for landslide hazard management in the West Coast region

The regional landslide susceptibility map and landslide catalogue have addressed some of the information gaps highlighted in the "West Coast Regional Council: Natural Hazards Review", (DTEC, 2002). This has helped the WCRC to meet its obligations (under the RMA) to provide as accurate and up to date information as possible relating to natural hazards.

Since this research was carried out from the offices of the WCRC, personal relationships between the researcher and the decision-makers of the region were established. This has enabled:

- The information transfer to be achieved without delay and with maximum effectiveness. For example, the landslide susceptibility map has already been used to guide preliminary decisions on Resource Consent applications for hydro-electric projects at Griffin Creek and Fairdown, and Building Consent applications at Karamea and Karoro.
- Sensible suggestions to be proposed (which integrate with current planning policy) relating to the meanings of the zones of the susceptibility map.

The delivery of educational workshops and the provision of a "user guide" have further encouraged the correct use of the new tools.

The limitations of the landslide hazard management tools contained in the thesis are presented and explained to avoid misinterpretation and misuse of the tools. The degree of confidence in the landslide susceptibility model is variable across the region, as shown in figure 7.5. Additionally, the predictive power of the susceptibility map is such that it can be expected to predict 60% of landslides in the top 30% of the susceptibility scores on the map with 70 % of future landslides expected to occur in the “very high” susceptibility zone. These levels of predictive power and data confidence should encourage the decision-makers of the region to use the susceptibility map to help develop sound landslide hazard management policy.

The landslide susceptibility map and landslide catalogue, when used together, provide decision- and policy-makers with an enhanced means of managing landslide hazards in the West Coast region. These tools represent a first, but fundamental step in land-use planning and set-up of landslide hazard management in the West Coast region. However, the real success of this work will only be realised if the decision-makers of the region continue to use these tools and develop land-use policies that reflect the information contained in the thesis.

## 7.8 Suggestions for further research

The landslide susceptibility map is intended to be used as a “first pass” assessment of landslide hazard in a particular area. This highlights certain areas that require more detailed, or site-specific, investigations to be carried out. For example, in Chapter 6 it was shown how the town of Granity would benefit from more detailed analysis of landslides, including assessments of probability of occurrence, expected size and run-out characteristics. This is true of any area of the region where infrastructure lies in, or very close to, the higher susceptibility zones.

In recent years, landslide dams in the West Coast region have gained much attention from researchers (e.g. Davies, 2002; Korup, 2005) who have highlighted the characteristics, and attempted to quantify, the hazard posed by this landslide phenomenon. The problems associated with poor availability of landslide inventory data have prevented a successful quantification of this hazard (Korup, 2005). However, it is feasible to assume that a suitable method could be developed to further analyse the landslide susceptibility map to predict the future locations of landslide dams and help to define or even quantify this hazard.

In this study, the study area was divided into the two sub areas (east of the Alpine fault and west of the Alpine fault), which allowed the creation of more accurate landslide susceptibility maps than would be possible by applying a single model to the whole region. This raises the question: "what is the ideal study area size to allow the creation of a robust model?" Further research comparing study area size to model robustness would help to define the ideal study area size for this kind of landslide susceptibility analysis.

GIS methodologies exist to relate debris-flow hazard to catchment geometry parameters (Welsh, 2008; Welsh and Davies, 2010), which suggests that these methodologies could be used in conjunction with the landslide susceptibility map to improve the debris-flow hazard characterisation in known debris-flow locations and identify new locations that are prone to debris-flow.

The landslide catalogue has certainly been under-utilised in this study. Considerable efforts were made to include as many landslide entries as possible, and attach useful information (such as preceding 24 hour rainfall amounts) to each entry. This has produced a useful tool in its own right. However, a detailed analysis of its properties may help to further characterise landslides and related phenomena, such as river bed aggradation. The spatio-temporal characteristics of landslide occurrences in the West Coast region could potentially be further defined by careful analysis of the catalogue. When used in conjunction with other studies, such as the "Global landslide catalogue for hazard applications" (Kirschbaum *et al.,* 2010), it may be possible to answer some of the questions relating to the effects on landslide frequency and distribution in the West Coast region due to global climate change.

The process of transferring the hazard information contained in this study to the decision-makers of the region has been outlined in chapter 6. However, the degree of information uptake and application of the landslide hazard tools to help improve landslide hazard management in the West Coast region remains to be seen. Recent research has highlighted the need for natural hazards research findings to be more effectively integrated into community planning and development initiatives

(Glavovic, *et al.,* 2010; Glavovic, 2010). This study was conducted with that in mind, but the actual effectiveness of this information transfer could be monitored and a strategy developed to assure the most effective means of information transfer from research to practice.

# Chapter 8. Summary and conclusions

## 8.1 Introduction

This chapter summarises the main findings and presents the conclusions of the research. The objective of this thesis was to improve the landslide hazard management abilities of the decision-makers of the region. To accomplish this, the following has been achieved:

1. The correlations between landslide occurrences in the West Coast region and the environmental conditions that control them have been established by means of a statistical landslide susceptibility assessment. This is displayed in the form of a landslide susceptibility map.
2. The map's predictive power has been tested so that it may be used with the correct levels of confidence.
3. An historic landslide catalogue has been compiled and presented in a way that it can be easily accessed and queried.
4. These tools have been delivered to the decision-makers of the region via a series of workshops.

## 8.2 Main findings

The primary goal of this thesis was to establish the relationship between landslides and the various environmental conditions that control them in the West Coast region. This has been achieved in the results chapter, but the fact remains that landslides are natural phenomena which are governed by very complex interactions of environmental variables within a system that can only ever be represented as an approximation of the actual processes. This approximation has been quantified by means of a validation, which illustrates the limitations of the landslide susceptibility model. Understanding the limitations of this (and any) model is essential when deciding on the level of confidence to apply to its output and will therefore govern the types of decisions that can be supported by it.

The landslide susceptibility map, for the western area, has an accuracy that predicts 40%of landslide occurrences in 20% of the map with the highest susceptibility scores and 80% of the landslides in 40% of the map with the highest susceptibility scores.

This indicates that these results can be used with a high degree of confidence. In comparison, the landslide susceptibility map, for the eastern area, has an accuracy that predicts 30%of landslide occurrences in 20% of the map with the highest susceptibility scores and 60% of the landslides in 40% of the map with the highest susceptibility scores. This indicates that the result for the eastern area should be used with a lower level of confidence. Since almost all the infrastructure elements in the region are positioned in the western area (to the west of the Alpine fault), this result is satisfactory.

The relationships established by means of a bivariate statistical analysis are certainly oversimplified. This is partly due to the assumption that the variables are conditionally independent of each other and partly due to the fact that landslide occurrence and behaviour is controlled by far more environmental variables than are represented herein. The application of the AHP successfully addresses the issue of assuming conditional independence and effectively ranks the importance of each factor in the control of landslides. This delivers superior results in terms of predictive power of the model, but adds an element of subjectivity to an otherwise purely objective statistical study. However, this point should not be seen as a detriment. Clearly, a high degree of understanding of the physical processes involved in landslides is required to conduct any study of landslide distribution. For example, the choice of thematic information to include in the statistical comparisons and the identification of landslides from API, both involve expert judgement. Therefore, an element of subjectivity will be introduced to the study, whether intentional or not.

In order to avoid misinterpretation, the study was conducted in accordance with the JTC-1 guidelines (Fell *et al.* 2008), which define the terminology, give guidance on scale and data requirements, and advise on the reliability, validity and limitations of the methods, used to conduct landslide susceptibility and hazard zoning. This enables the findings of this thesis to be compared to other regions and be effectively used for landslide hazard management purposes by the decision-makers of the region.

The research was conducted from the offices of WCRC in Paroa. This allowed sensible suggestions to be proposed (which integrate with current planning policy) relating to the meanings of the zones of the susceptibility map. Additionally, the information contained in the thesis was transferred to the decision-makers of the region without delay and with maximum effectiveness.

## 8.3 Conclusion

This thesis has furthered the understanding of landslide distribution in the West Coast region. The use of bivariate statistics and the analytical hierarchy process has been proven to be a successful technique to create a landslide susceptibility map for the West Coast region. The methods used have been tested and validated to enable the end users of the map to apply the correct level of confidence to the information it displays. Additionally, a landslide catalogue has been compiled, which can be used to further define the landslide characteristics in the region.

The landslide susceptibility map and landslide catalogue are two new tools that will help the decision- and policy-makers of the West Coast region to manage the landslide hazard more effectively. These tools represent a first, but fundamental step in land-use planning and set-up of landslide hazard management in the West Coast region.

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# Appendices

**Appendix A:**

DVD ROM containing:

1. ARC GIS 9.3 Geodatabase (Data_layers) containing all the thematic factor maps including the catalogue and the landslide inventory
2. ARC GIS 9.3 Geodatabase (EQ_generated_ls) containing experimental earthquake generated landslide susceptibility maps
3. File folder (Catalogue) containing Microsoft Excel spreadsheet of the Landslide Catalogue (Catalogue.xlsx)
4. File folder (Susc_maps) containing ARC GIS 9.3 files:
    1. LSI map of the Eastern area generated using the weighting factor method only (east_sus_wfm).
    2. LSI map of the Western area generated using the weighting factor method only (west_sus_wfm)
    3. LSI map of the Eastern area generated using the AHP method (east_sus_ahp).
    4. LSI map of the Western area generated using the AHP method (west_sus_ahp).
    5. Zoned susceptibility map of the whole region (ls_susc_map).
    6. Zoned susceptibility map of the whole region, in GeoTIF format (zoned_susc_map_GeoTIF)

**Appendix B:**

A landslide susceptibility map and landslide catalogue for the West Coast region. The user guide.

As supplied to the decision-makers of the West Coast Region.

# A GIS approach to landslide hazard management for the West Coast region, New Zealand.

Kevin A. England

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**Executive summary**

This paper presents two tools for landslide hazard management in the West Coast region of New Zealand. As part of a Masters Degree Thesis entitled “A landslide susceptibility model for the West Coast Region, New Zealand”, a landslide susceptibility map and a landslide catalogue have been produced. This paper explains the research methodology, limitations and intended uses of these tools.

In order to avoid misinterpretation the study has been carried out in compliance with the “Guidelines for landslide susceptibility, hazard and risk zoning for land use planning”, which was published in 2008 by the Joint Technical Committee on Landslides and Engineered Slopes.

This study identifies areas that are susceptible to rainfall triggered landslides in the West Coast region. The landslide susceptibility model was produced using bivariate statistics and the analytical hierarchy process. It has an accuracy that predicts 80% of all the landslides in the top 40% of the susceptibility scores on the map. As part of this process, 3221 rainfall triggered landslides and 522 earthquake (or other trigger) triggered landslides have been mapped and digitised into a GIS. In parallel with this, a descriptive historical catalogue of 1987 landslides has been compiled from all the available sources. These two tools provide decision-makers with an enhanced means of managing landslide hazards in the West Coast region.

# 1. Introduction

## 1.1 Background

Landslides, in their various forms, are a common hazard in mountainous terrain, especially in seismically active areas and regions of high rainfall. The West Coast Region of New Zealand is dissected by many active faults, experiences frequent earthquakes and in many locations annual rainfall exceeds 10m. Consequently, landslides are widespread natural phenomena in the region and since European settlement began in the late $19^{th}$ century have been responsible for 27 deaths, along with frequent damages to road and rail infrastructure, settlements and agricultural land (Benn, 2005). The continuing residential and commercial development of hilly country throughout the region combined with the increasing value of real estate has highlighted the need for better understanding of landslide occurrence and distribution.

This study identifies areas that are susceptible to rainfall triggered landslides in the West Coast Region. It also presents historic landslide data from the most complete catalogue of landslides in the region. When this information is compared to infrastructure and land use information held at the Regional and District Councils it allows the identification of sites most at risk from landslide damage.

In order to avoid misinterpretation the study has been carried out in compliance with the "Guidelines for landslide susceptibility, hazard and risk zoning for land use planning", which was published in 2008 by the Joint Technical Committee on Landslides and Engineered Slopes (Fell *et al.,* 2008). In 2007 GNS Science published the "Guidelines for assessing planning policy and consent requirements for landslide prone land" (Saunders and Glassey, 2007), which has become the standard reference document for Council Planners in matters relating to landslide hazard management. These guidelines should be used in combination with the hazard information contained in this study. This will help to reduce the costs associated with landslide damage and aid in disaster reduction.

## 1.2 Terminology

In this study a landslide is defined as a gravity driven down-slope movement of soil, debris or rock. The landslide susceptibility map does not differentiate between the various types of landslide. However, the landslide catalogue describes the different forms of landslides based on the classification system designed by Cruden and Varnes (1996), which has become accepted as the standard means of describing the form of landslides. Table 1 shows this classification

<table>
<tr><th colspan="2" rowspan="3">Type of movement</th><th colspan="3">Type of material</th></tr>
<tr><th rowspan="2">Bedrock</th><th colspan="2">Engineering soils</th></tr>
<tr><th>Predominantly coarse</th><th>Predominantly fine</th></tr>
<tr><td colspan="2">Falls</td><td>Rock fall</td><td>Debris fall</td><td>Earth fall</td></tr>
<tr><td colspan="2">Topples</td><td>Rock topple</td><td>Debris topple</td><td>Earth topple</td></tr>
<tr><td rowspan="2">Slides</td><td>Rotational</td><td rowspan="2">Rock slide</td><td rowspan="2">Debris slide</td><td rowspan="2">Earth slide</td></tr>
<tr><td>Translational</td></tr>
<tr><td colspan="2">Lateral spreads</td><td>Rock spread</td><td>Debris spread</td><td>Earth spread</td></tr>
<tr><td colspan="2">Flows</td><td>Rock flow</td><td>Debris flow</td><td>Earth flow</td></tr>
<tr><td colspan="5">Complex: a combination of two or more principal types of movement</td></tr>
</table>

**Table 2 Types of landslides. Abbreviated version of Cruden and Varnes' classification of landslide types (Cruden and Varnes, 1996).**

The use of Geographic Information Systems (GIS) requires specific terms, so a glossary of these terms and the terms used to describe the landslide hazard is included as an appendix to this paper.

### 1.3 Overview

The problem of landscape instability and its effects on infrastructure and people has traditionally been approached in a deterministic manner, where site specific investigations are conducted to determine the stability of a particular area of interest. In contrast to the deterministic approach, this study has used a statistical modelling technique to define areas that are more or less likely to experience landslides. The output of this statistical model is a “landslide susceptibility map”, which depicts areas likely to have landslides in the future by correlating some of the principal factors that contribute to landslides with the past distribution of landslides (Yalcin, 2008). It relies on the trusted geological principle that “the past and the present are the keys to the future”. That is, future landslides are most likely to occur under the same conditions that led to past and present landslides (Dai and Lee, 2002).

The first, and most important, stage of landslide susceptibility modelling is to produce a landslide inventory map. Once this has been achieved the spatial characteristics of the landslide distribution can be explored. The aerial photograph archive at the WCRC provided the majority of the input data, but other sources, such as DoC’s photo archives, field investigations and Google Earth were used where required.

Validation of the landslide susceptibility map was carried out using a new set of aerial photography obtained from the Animal Health Board. The predictive power of the map was tested using the success rate curve method of Chung and Fabbri (2003).

The landslide susceptibility map, in combination with the landslide inventory map can be used to better understand the potential for future landslide occurrences in the West Coast Region. In addition to this, an historical catalogue of damaging landslides has been compiled and stored in a format that is easily viewable in database or digital map format. These tools can be effectively used by decision-makers to aid in landslide hazard management. However, it does not replace the need for site specific geotechnical investigations.

This manual explains:

- the methodology used to produce the landslide susceptibility map and the landslide catalogue
- The limitations of these tools
- The most appropriate means of using the tools

Detailed descriptions of the mathematical formulations and techniques used for the statistical analysis and modelling can be found in the thesis entitled “A landslide susceptibility model for the West Coast Region, New Zealand” (England, 2011)

# 2 The landslide susceptibility map

## 2.1. Methodology

This study utilises the “weights of evidence” method, which was first developed by Bonham Carter (1994), for use in mineral potential assessment for the mining industry. Since Van Westen (2003) applied it to landslide susceptibility analysis, it has been successfully used for this purpose in many different and diverse study areas (Dai and Lee, 2002; Gullà *et al., 2008*, etc.). More recently, the analytical hierarchy process (AHP) of Saaty (1978) has been applied to the problem of landslide susceptibility modelling, to refine and improve the results of the weights of evidence method (Boroushaki and Malczewski, 2008, Yalcin, 2008, etc.).

In this study, both of these methods have been used, the results compared, and the most appropriate technique chosen for the final landslide susceptibility map.

During early experimentation (in this study) with these techniques it became obvious that the terrain variables that act as control factors in the occurrence of landsides are very different across the study area. One of the criticisms of this type of modelling is that a high degree of simplification is required (Fell, *et al.,* 2008, Dai and Lee, 2002) especially in large study areas such as the West Coast region. The geologic, tectonic, geomorphic and environmental conditions in the coastal plains are very different than those present in the Southern Alps. Correspondingly, the environmental controls on landsliding are also different and the distributions of landslide occurrences reflect this. For this reason it was decided that the study area be divided into 2 distinct areas and the modelling of landslide behaviour and distribution was handled separately in these two areas. The Alpine fault is the largest tectonic feature in the West Coast region, and conveniently separates the region into 2 areas:

1. East of the Alpine Fault. The Southern Alps, comprising mainly of schist.
2. West of the Alpine Fault. The coastal plains and the granitic basement rocks of the West Coast Region, including the Paparoas and mountains in the Buller district.

Figure 1 illustrates the steps followed in this study to produce the final landslide susceptibility map of the West Coast region.

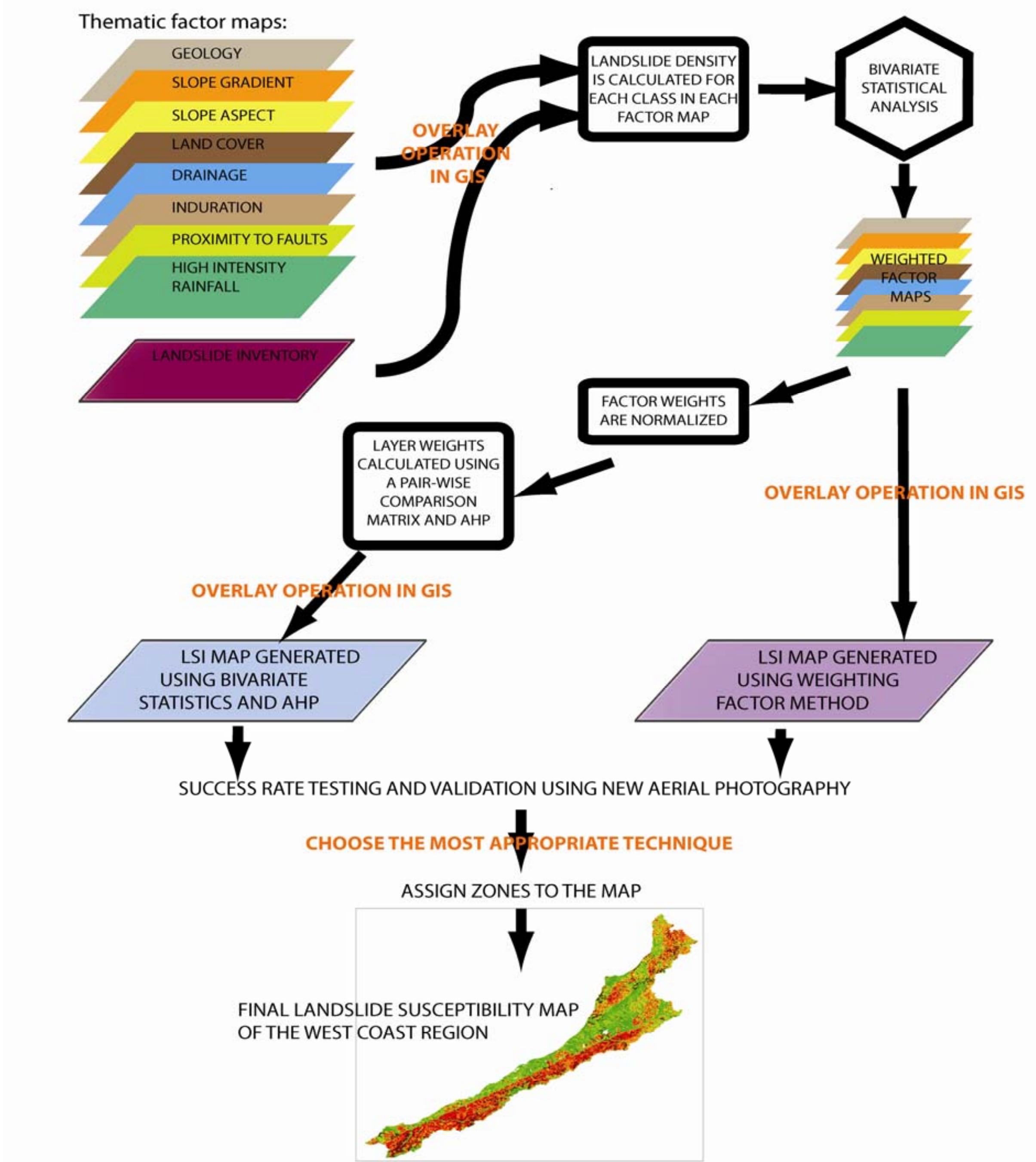


**Figure 2 Flow diagram representing the steps used to produce a landslide susceptibility map for the West Coast region.**

In total, 2566 rainfall triggered landslides covering a combined area of 61.4km$^2$ were mapped from aerial photography, satellite photography, direct field observations and extracted from other research (Smith, 2004, GNS 2010) to form the landslide inventory layer. 8 factor maps representing the factors deemed to be influential in the control of landsliding were prepared in a GIS and categorized into sensible classes to facilitate direct statistical comparisons with the landslide inventory layer. These factor maps are:

1. **Geology.** The geologic units contained within the 6 QMAP's for the West Coast Region (Nelson, Greymouth, Kaikoura, Aoraki, Haast and Wakatipu) were imported into a GIS and extracted to produce a regional geology map. The resulting 45 rock types were then grouped into the 10 classes.
2. **Slope gradient.** A categorized slope gradient map was generated from a high resolution digital elevation model (DEM). The DEM used in this study was prepared for the Foundation for Research, Science and Technology in 2002. Land Information New Zealand provided Landcare Research with photogrammetrically derived 20m contours, spot heights, lake shorelines and coastlines, which was then used to generate a 25m cell size DEM using Landcare Research's internally developed software as described in Barringer *et al.* (2002). This DEM is available as a commercial product and was used for this study under licence for research purposes only at the University of Canterbury, Department of Geological Sciences.
3. **Slope aspect.** The same DEM as described above was used to generate a slope aspect layer.
4. **Land cover.** The New Zealand Climate Change Office and the Ministry for the Environment publish a Land Cover Database which is a thematic classification of 43 land cover and land use classes in New Zealand. It primarily uses SPOT 5 and Landsat 7 satellite imagery to identify the different land cover classes. The first Land Cover Database (LCDB1) was completed in 2000 and the second (LCDB2) was released in 2004, and was intended as a formal method of tracking climate change related land use/land cover changes (New Zealand Climate Change Office, 2002). This study uses LCDB2 under licence from WCRC. Land cover classes that do not relate to landsliding were removed from the map, so areas of open water, coastal sand and gravel, river bed gravel, etc have been excluded from the landslide susceptibility assessment. Similarly, areas of permanent snow and ice have been removed from the land cover thematic factor map. This was done because these areas are subject to a very different set of rules governing landscape stability, and this thesis does not make an attempt to classify snow and ice avalanches, or glacial collapse. The remaining land cover classes were grouped into 10 generalized classes.
5. **Soil drainage.** Land Environments of New Zealand (LENZ) is a land classification system designed by Landcare Research, Ltd. with the underlying data layers being available for research purposes as described in Leathwick *et al.* (2003). It uses the New Zealand Land

Resource Inventory and the New Zealand Soils Database, in combination with field mapping to derive values of soil properties on a national scale. This map classifies soil drainage properties into 5 groups, so no further processing was necessary for use in this study.

6. **Soil Induration.** The LENZ data layers also contain information relating to soil induration. This map classifies soil induration properties into 5 groups, so no further processing was necessary for use in this study.
7. **Proximity to faults.** The faults plotted on the 6 QMAP's for the region were extracted to form a regional fault map. Buffers of 100m, 1000m and 3000m were applied to all the faults thus dividing the region into 4 classes.
8. **High intensity rainfall.** Since landslides are usually triggered by heavy rainfall a map of maximum expected rainfall in 24 hours for a specific return period rainstorm is more useful than a traditional annual rainfall map (Van Westen *et al.,* 2008). Fortunately, Craig Thompson of the National Institute of Water and Atmospheric Research (NIWA) developed the high intensity rainfall design system (HIRDS), which is a computer-based procedure for estimating design rainfalls in New Zealand (Thompson, 2002). The HIRDS map shows design maximum expected rainfall during a 10 year return period rainstorm. The continuous raster map was reclassified into 9 convenient classes.

These 8 factor maps were individually compared to the landslide inventory layer and a bivariate statistical analysis carried out to establish the correlation between landslides and the individual classes contained within each factor map. The factor map classes were reclassified using the weighting scores derived from this analysis and all 8 maps numerically added to produce a landslide susceptibility index (LSI) map. This is the weighting factor method of Bonham-Carter (1994). One of the criticisms of the weighting factor method is that it assumes that the various factors are conditionally independent of each other (Dahal *et al.*2008). Since the factor maps are analysed separately, the relative importance of factors within a single map (ie, whether granite is more or less susceptible to landsliding than schist for a geology map) is established, but the relationship between the separate maps is not established by this technique.

The AHP has been applied successfully to landslide susceptibility modelling by many authors (Dai *et al.,* 2001; Komac, 2004; Yalcin, 2008; Liu and Chen, 2003, etc.), and is used in this study to establish the relative importance of the separate factor maps in the control of landslide occurrence. These two techniques were trialled and the results tested and compared. The most appropriate technique was then chosen and the resulting landslide susceptibility index map was then zoned and published for use in landslide hazard management in the West Coast Region.

The usefulness of a susceptibility map is greatly increased when it is divided into five zones: very low, low, moderate, high and very high susceptibility to landsliding (Fell *et al.*, 2008). This zoning is accomplished by assigning LSI values to the boundaries between the zones such that a certain proportion of the mapped landslides fall within each zone.

Rules relating to land use and development planning can be attached to each of the zones and the boundaries are easily visible. Also, the spatial characteristics of the zones can be quantitatively explored giving more meaning to the classification of the zones. Figure 2 shows the visual difference between an LSI map and a zoned landslide susceptibility map.

The landslide susceptibility map should be viewed in combination with the landslide inventory. The landslide inventory contains polygons of mapped landslides and is therefore useful in identifying areas that have experienced landslides in the past. Rainfall triggered landslides are displayed separately from the larger, often prehistoric, earthquake triggered (or unknown trigger) landslides.

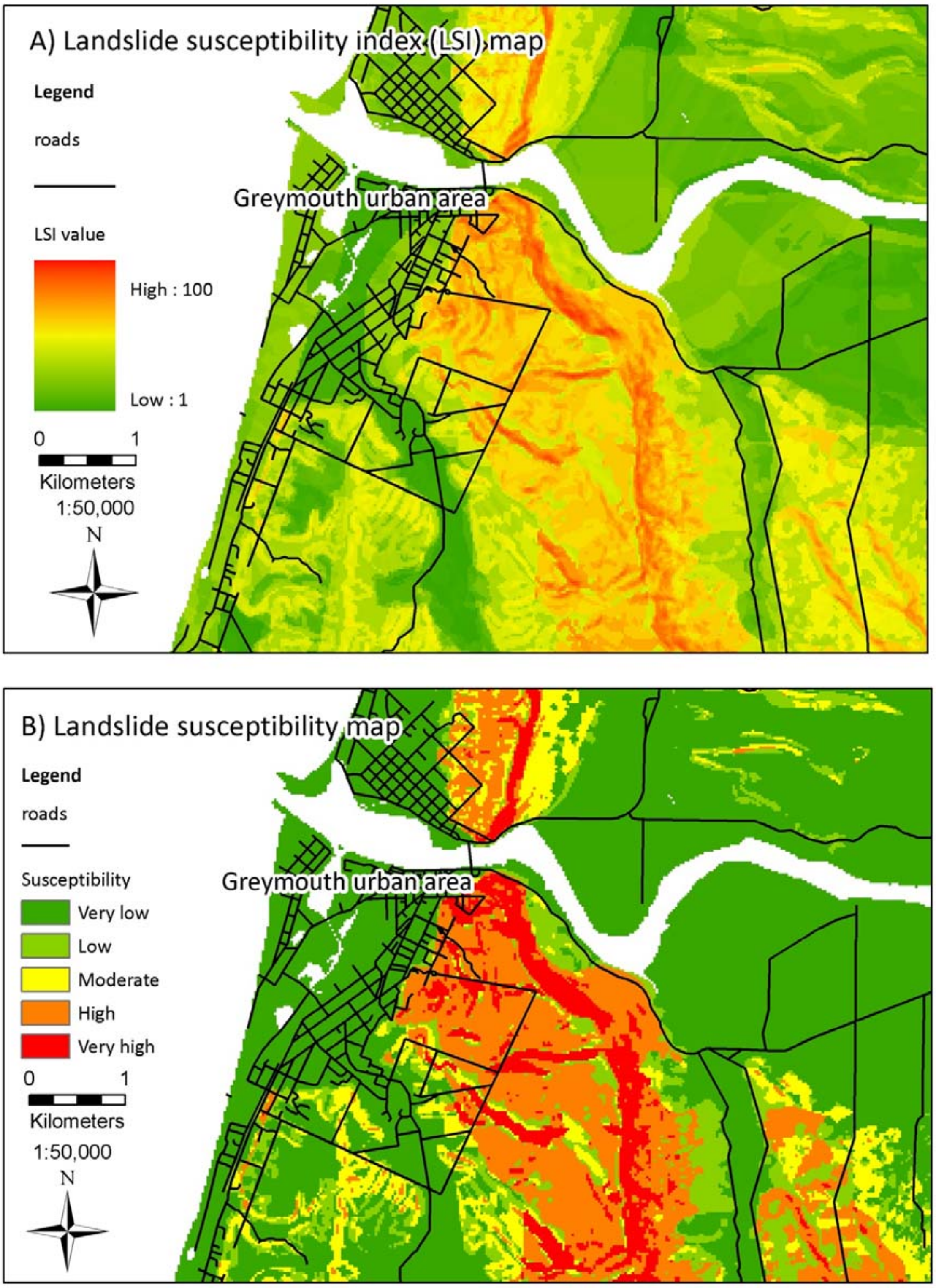


**Figure 3. A comparison of an LSI map, with a continuous variable (A) and a zoned landslide susceptibility map (B)**

## 2.2 Success rate testing and validation

The above procedure produced 4 LSI maps:

- LSI map of the Eastern area generated using the weighting factor method (WFM_E).
- LSI map of the Western area generated using the weighting factor method (WFM_W).
- LSI map of the Eastern area generated using the analytical hierarchy process method (AHP_E).
- LSI map of the Western area generated using the analytical hierarchy process method (AHP_W).

These maps were tested for their predictive power using the success rate curve method of Chung and Fabbri (2003). The success rate is calculated by ordering the pixels of the LSI maps and grouping into 100 classes from high to low values, in a quantile distribution based on the frequency information from the histogram of their distribution. After that, a landslide inventory derived from a new set of aerial photography (that was not used in the original analysis) is overlayed with the categorised LSI map and the joint frequency is then plotted on a scatter graph (Chung and Fabbri, 2003; Frattini *et al.* 2010). A hypothetical success rate curve coinciding with a diagonal from 0 to 100 would be equivalent to a totally random prediction. The further up and away the success rate curve is from that diagonal, the better the predictive value of the map. Likewise, the greater the gradient in the first part of the curve the greater its predictive capability (Chung and Fabbri, 2003; Remondo *et al.*2003). Figure 3.shows the validation success rate curves for the 4 susceptibility maps. Clearly, the maps generated using the AHP method show a greater predictive accuracy than the ones which use the weighting factor method alone.

From this it can be seen that in the case of AHP_W, 40% of the landslides occurred in 20% of the map with the highest susceptibility values and 80% of the landslides occurred in 40% of the map with the highest susceptibility values.

The susceptibility maps for the eastern area (Southern Alps) show a marginally better fit than the western maps in the first part of the curve, but towards the ends of the curves it is clear that the eastern maps do not perform as well. For example, in the case of both western maps, all the validation landslides (100%) occurred in 70% of the map, but for the case of the eastern maps there were still landslides occurring in the lowest 10% of the susceptibility classes.

The area under the curve for the AHP maps is significantly larger than for the WFM maps, which proves the superior predictive capability of the AHP method in generating landslide susceptibility maps. On the basis of these results, the most appropriate maps to use for landslide hazard management in the West Coast region are the ones generated using bivariate statistics and the analytical hierarchy process.

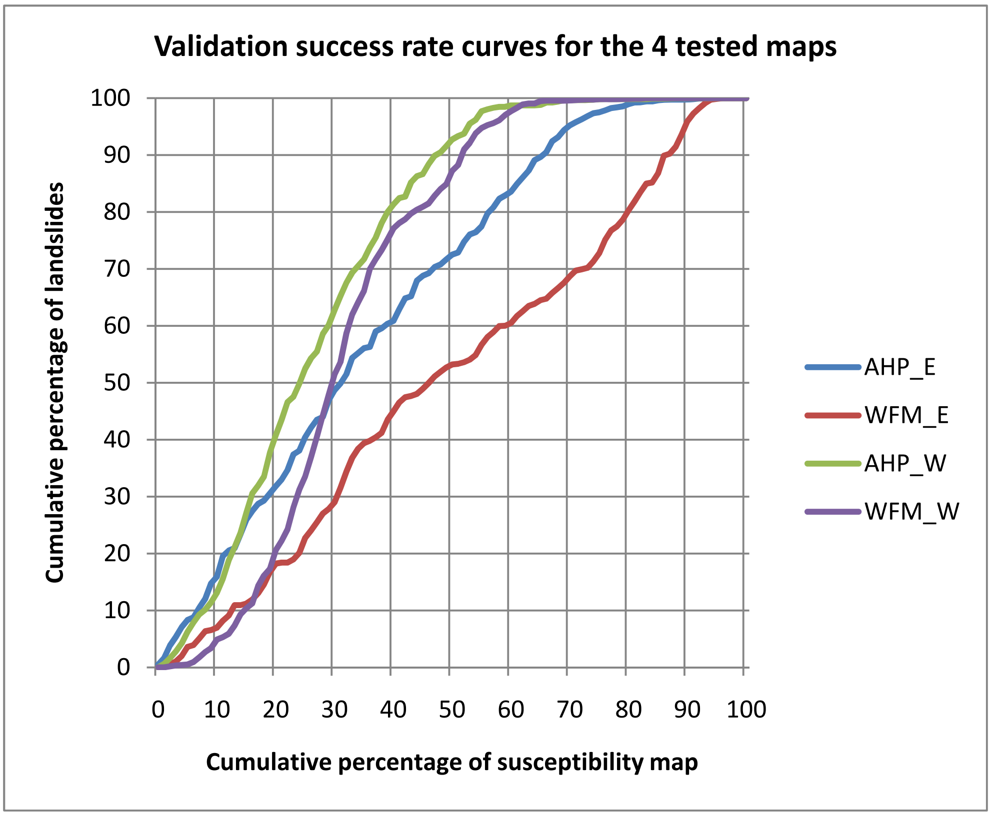


**Figure 4. Validation success rates for the 4 LSI maps of the West Coast Region**

### 2.3 Assigning zones to the maps

By extracting all the landslide polygons (from the original dataset and the validation dataset) from the LSI map and ordering those pixels from high to low it is possible to find the corresponding LSI value that relates to a certain percentage of landslides. Table 2 shows the percentage of landslides and the LSI values that were used to assign the zones to the final susceptibility map. So, 70 % of landslides occur in the very high susceptibility zone, 22% in the high susceptibility zone, etc.

**Table 2. Percentage of landslides in each susceptibility zone and their corresponding LSI values.**

| Susceptibility zone | Percentage of all landslides | LSI values | |
|---|---|---|---|
| | | East | West |
| Very low | 1 | 0-7 | 0-24 |
| Low | 2 | 8-15 | 25-33 |
| Moderate | 5 | 16-29 | 34-44 |
| High | 22 | 30-58 | 45-70 |
| Very high | 70 | 59-100 | 71-100 |

Figure 2 (page 10) illustrates the difference between an LSI map, showing a continuous variable of landslide susceptibility index scores and a susceptibility map, which has 5 distinct zones.

Once the zones are established the spatial characteristics of these can be explored which will help in the final use of the susceptibility map.

Table 3 illustrates the spatial distribution of the 5 susceptibility zones. It is worth noting here that 34% of the area to the East of the Alpine fault is classed as “very high” susceptibility to landsliding, whereas the corresponding zone on the Western side of the fault is only 24% of the land area. This is in accordance with the expected results.

**Table 3. Area of the region covered by the different susceptibility zones.**

| Susceptibility zone | % of Eastern area of West Coast Region | % of Western area of West Coast Region | % of West Coast Region |
|---|---|---|---|
| Very low | 5.72 | 27.20 | 19.45 |
| Low | 9.58 | 11.10 | 10.55 |
| Moderate | 18.09 | 11.61 | 13.95 |
| High | 32.62 | 25.83 | 28.28 |
| Very high | 34.00 | 24.26 | 27.78 |

Further analysis of the spatial characteristics of the map is useful to define the meanings of the zones. Table 4 shows the land area, landslide density and % of the land surface affected by landslides in each zone.

**Table 4. Spatial characteristics of the landslide susceptibility zones.**

| Susceptibility zone | Area/$km^2$ | Landslide density: number of landslides/10$km^2$ | % of land surface affected by landslides |
|---|---|---|---|
| Very low | 4302 | 0.0 | 0.003 |
| Low | 2334 | 0.3 | 0.012 |
| Moderate | 3085 | 0.6 | 0.056 |
| High | 6256 | 1.5 | 0.218 |
| Very high | 6145 | 6.8 | 0.913 |

## 2.4 Limitations of the landslide susceptibility model

By definition, a landslide susceptibility map does not define the temporal characteristics of the occurrence of landslides (Fell *et al.*, 2004) Since timeframe is an essential part of the risk equation, a susceptibility map should not be used for detailed risk assessments.

This is a regional scale study and should be used as such. The scale used for the initial landslide mapping was 1:25,000 so the susceptibility maps should be viewed at that scale. The minimum mapping unit in this study is the 25m x 25m pixel, so this mapping roughness should also be taken into account when using the susceptibility map.

This study models the landscape's susceptibility to rainfall triggered landslides. It does not delineate the areas that are more or less likely to experience land instability issues during an earthquake.

Any landslide susceptibility study has a certain level of uncertainty (Guzetti, *et al.*, 2006). Sources of uncertainty include:

- Errors and incompleteness in the landslide inventory
- Errors in the thematic factor maps
- Limitations in the technique chosen for the susceptibility analysis
- The inherent natural variability of the landslide phenomena

With regard to the sources of uncertainty, the introduced error derived from an incomplete landslide inventory is certainly an area of concern for this (and any landslide susceptibility) study. Due to the partial coverage of aerial photography for the region, the landslide inventory is incomplete. This will be true of all landslide susceptibility models, and must be taken into account when using the final map. The thematic factor maps are the best available, but due to scale and mapping roughness there may be errors introduced to the model from these sources.

This model has an accuracy that predicts 80% of the landslides in the top 40% of the susceptibility scores. However, the model can not claim to accurately delineate the probability of occurrence in each of the susceptibility zones.

As with any natural process, landslides do not occur with a regularity that enables complete prediction of their behaviour. This model should be used with this in mind.

## 3. The historic landslide catalogue

### 3.1 Methodology

An historical catalogue of 1987 landslides in the region was compiled from all the available sources as described in table 5. For all entries, x,y coordinate pairs were assigned and where possible, 24 hour preceding rainfall amounts were added for rainfall generated landslides and volume estimations made from the descriptions. In contrast to the landslide susceptibility map, which models the occurrence of landslides triggered by rainfall alone, the landslide catalogue details all landslides regardless of the trigger mechanism.

The catalogue can then be displayed in a GIS to be used in further classifying the landslide characteristics for a selected area. Interrogation of the catalogue can also be used to put a temporal dimension to the prediction of future landsliding in certain cases.

**Table 5. Pre-existing landslide catalogues used in this study.**

| Study | Geographic area | Dates | Sub-sources | Comments |
|---|---|---|---|---|
| Smith, 2004. | Otira-Arthur's Pass to Jacksons on SH73.<br>Taramakau valley-Jacksons to Greymouth on SH73 and SH6.<br>Arnold and Grey valleys-Jacksons to Greymouth on Midland Railway line and SH7. | 27/02/1918 to 19/02/2003 | Transit NZ Ltd.<br>Ministry of Works.<br>Grey District Council.<br>Transfield Ltd.<br>Tranzrail Ltd.<br>WCRC natural Hazards Review | Study area limited to the transportation corridors from Arthur's Pass to Greymouth. |

| Study | Geographic area | Dates | Sub-sources | Comments |
|---|---|---|---|---|
| Cooper, 2000. | Buller District. | 1999 | Buller District Council | No information on dates of failure, so simply shows a "snapshot" of observable landslides during the study period. Also, limited to personal observations by the author. |
| GNS landslide catalogue. | Nationwide, so covers the entirety of this study area. | 12/08/1997 to 12/01/2009 | National and local newspapers. Hazardwatch. National Radio. Original research | Limited to slides >1km$^2$. Not focused on infrastructure. |
| WCRC landslide archive. | West Coast Region | 13/01/1945 to 29/07/2009 | Benn, 1990. Benn, 1992. Patterson and Berrell, 1995. Greymouth Evening Sar. Westport News. Lowe, 2001. Fulton, 2004. Power and Anderson, 1992. The Press. Patterson and Bourne-Webb, 1994 Johnston, 1971 Buller District Council. Westland District Council. Grey District Council. Personal observations by WCRC Natural Hazards Analyst, M. Trayes. | Sporadic entries-some years missing. Essentially based on Benn's (1990) inventory, which was derived from a flood hazard study. Newspaper archives formed the bulk of Benn's (1990) study, which did not include the Westport News archives. Only recent entries from Westport News are included. |
| OPUS Consultants | West Coast Region, State Highway network | 08/01/2004 to 17/11/2009 | Roading Contractors | Data limited to date, location and volume of material transported away from the site. No description of trigger or actual movement characteristics. |
| OnTrack | West Coast Region, Railway Network: Midland line, Stillwater-Westport line, Rapahoe line, Hokitika Industrial line. | 01/01/2005 to 11/01/2010 | Locomotive Engineers, maintenance staff. | Results of a search of the OnTrack Incident Reporting System (IRIS) with landslide, slip and subsidence as keywords. |

Further additions to this catalogue were accomplished by searching the archives of the Westport News at the Westport News offices in Westport, searching the archives of the Grey Star and the Hokitika Guardian at the Grey Star offices in Greymouth. Personally observed landslides were included wherever possible.

Each catalogue entry is identified by a unique identification number (ID number) and the following fields have been populated to give as complete a record of the landslide events as possible:

- Date. Essential for calculating magnitude/frequency relationships and temporal distribution patterns.
- Location. A descriptive term is included and the corresponding Easting and Northing was recorded to allow display in GIS. Where coordinate pairs were not recorded a search of the descriptive names of landslide locations on standard topographic maps, internet searches and local knowledge was used to assign coordinate pairs where possible. For entries concerning road and railway records the calculation of coordinates from Exact Road Positions (ERP) locations or Railway Miles locations was possible using the Calibrate Routes tool in ArcGIS toolbox.
- Description. A brief description of the landslide was included where the observer had recorded this. Unfortunately, this field is blank in many cases as the observer simply records the date, damage and location.
- Type. Slope movement classification was included where the description was adequate. In the interests of uniformity of terminology between studies, the classification system of Cruden and Varnes' (1998) was used and the abbreviations used in the catalogue are as follows:
  Rock fall (RF), Debris fall (DF), Earth fall (EF), Rock topple (RT), Debris topple (DT), Earth topple (ET), Rock slide (RS), Debris slide (DS), Earth slide (ES), Rock flow (RFL), Debris flow (DFL), Earth flow (EFL)
- Trigger information is recorded where possible and has been divided into rainfall generated (R), earthquake generated (EQ), erosion by river or coastal action (E), anthropogenically generated (A) and unknown (U).
- 24 hour rainfall amount was recorded for rainfall generated landslides. Rainfall records were obtained from the "Hilltop" meteorological database held and maintained by the WCRC. This database holds rainfall records from a network of gauges maintained and operated by the MetService, NIWA, WCRC and BDC. Records from 2 gauge stations owned and maintained by Solid Energy at Stockton were also used. Figures for the preceding 24hr period are presented. Database entries are generally by date only, with no time information, so a period of 12 noon on the preceding day to 12noon on the day of the landslide was used as the 24 hour rainfall figure. The gauge station closest to the landslide event was used regardless of prevailing wind and incident weather direction.
- EQ magnitude was recorded for earthquake generated landslides.
- Volume of slip material was estimated in cubic meters and recorded where possible.
- Additional comments were also recorded.
- Deaths. Where a landslide has resulted in death this has been recorded.
- Data source and sub-source has also been recorded. For example, if a record of a landslide was found in the Greymouth Evening Star and included in Smith's (2004) inventory it will be recorded as Greymouth Evening Star in "Source" and Emily Smith as the "Sub-source".

The resultant landslide catalogue is by far the most complete record of damaging landslides ever compiled for the West Coast region. This should be updated by the Natural Hazards Analyst at the WCRC and forwarded annually to all interested parties.

It can be used to illustrate the history and character of landslides for a selected area, or to give regional trends of landslide types, rainfall trigger levels, etc.

### 3.2 Limitations of the landslide catalogue

The landslide catalogue relies on reporting of incidents, so will be incomplete to varying degrees depending on the research efforts of the people who compile and maintain it.

Also, the reporting of landslide occurrences will often be carried out by people who are untrained in the observation of landslides, or who are reporting them for purposes other than landslide hazard management. For example, many of the landslides included in the landslide catalogue were taken from newspaper articles. These entries often do not contain volumes, landslide type, or other pertinent information. Similarly, a roading contractor who reports on a landslide may give a reasonable estimate of the volume and type of material, but almost certainly will not give an accurate description of the type of failure.

## 4. Use of these tools for landslide hazard management in the West Coast Region.

Broadly, the Resource Management Act (RMA) requires for Regional and District Councils to identify and avoid or mitigate natural hazards via a self managed suite of policies, plans and building and land-use consent approval processes. The Civil Defence Emergency Management Act 2002 (CDEMA) supports these planning provisions and aims to build community resilience, through the implementation of the reduction, readiness, response and recovery (4R's) emergency management approach (Glavovic, 2010). When viewed as a whole, these legislative provisions and the hazard information contained in this study provide a solid practical, policy and legal foundation which will enable local government planners to avoid or mitigate landslide hazard risks and help build sustainable, hazard resilient communities in the West Coast Region. In addition to this, these tools can also be used by CDEM groups, lifelines providers, property developers and individuals to help make better informed decisions relating to landslide hazard management.

The landslide susceptibility map was generated in ARC GIS 9.3, so it can easily be viewed on this platform. It is also possible to import the map into other display programs such as Map

TV and Landscape, which are more widely used at the Councils. This is also true of the landslide catalogue which can additionally be explored as a database or spreadsheet.

The zones of the landslide susceptibility map range from very low to very high susceptibility to landslides. The quantification of these zones is achieved by assigning the zone boundaries such that a certain percentage of all landslides in the region are expected to occur in each zone. This is described in table 2. The spatial characteristics of these zones are described in table 4.

The landslide susceptibility zones, when used in combination with asset information held at the councils, will be useful in making land use change decisions. For example, different levels of hazard can be acceptable to various elements at risk depending on the consequences of a landslide occurring at a particular site (Saunders and Glassey, 2007). To classify buildings, in terms of elements at risk, a classification of Building Importance Category (BIC) is one option that can be used. The most appropriate system is the Australia/New Zealand Standard for Structural Design Actions, Part 0 General Principles (AS/NZS 1170.0:2002). This is illustrated in table 6. This classification does not cover roads, bridges, or other essential infrastructure, but these items could be placed into a BIC category based on the relative importance of the item in question.

Table 6. Building Importance Categories: a modified version of New Zealand Loading Standard classifications (AS/NZS 1170.0:2002). Taken from Saunders and Glassey, 2007.

| Building Importance Category (BIC) | Description | Examples |
|---|---|---|
| 1 | Low consequence for loss of human life, or small or moderate economic, social, or environmental consequences. | Structures with a total floor area of less than 30m2<br>Farm buildings, isolated structures, towers in rural situations<br>Fences, masts, walls, in-ground swimming pools |
| 2a | Medium consequence for loss of human life, or considerable economic, social, or environmental consequences | Timber framed single-storey dwellings |
| 2b | (As above) | Timber framed houses of plan area more than 300m2<br>Houses outside the scope of NZS3604 “Timber Framed Buildings”<br>Multi-occupancy residential, commercial (including shops), industrial, office and retailing buildings designed to accommodate less than 5,000 people and also those less than 10,000m2 gross area. |

| | | |
|---|---|---|
| | | Public assembly buildings, theatres and cinemas of less than 1000m2<br><br>Car parking buildings |

| Building Importance Category (BIC) | Description | Examples |
| --- | --- | --- |
| 3 | High consequence for loss of human life, or very great economic, social, or environmental consequences (affecting crowds) | Emergency medical and other emergency facilities not designated as post disaster facilities<br>Buildings where more than 300 people can congregate in one area<br>Buildings and facilities with primary school, secondary school or day care facilities with capacity greater than 250<br>Buildings and facilities with capacity greater than 500 for colleges or adult education facilities<br>Health care facilities with a capacity of 50 or more residents but not having surgery or emergency treatment facilities<br>Airport terminals, principal railway stations, with a capacity of more than 250 people<br>Any occupancy with an occupancy load greater than 5,000<br>Power generating facilities, water treatment and waste water treatment facilities and other public utilities not included in Building Importance Category (BIC) 4<br>Buildings and facilities not included in BIC 4 containing hazardous materials capable of causing hazardous conditions that do not extend beyond the property boundaries |
| 4 | High consequence for loss of human life, or very great economic, social, or environmental consequences (post disaster functions) | Buildings and facilities designated as essential facilities<br>Buildings and facilities with special post-disaster function<br>Medical emergency or surgical facilities<br>Emergency service facilities such as fire, police stations and emergency vehicle garages<br>Utilities required as backup for buildings and facilities of importance level 4<br>Designated emergency shelters<br>Designated emergency centres and ancillary facilities<br>Buildings and facilities containing hazardous materials capable of causing hazardous conditions that extend beyond the property boundaries |
| 5 | Circumstances where reliability must be set on a case by case basis | Large dams, extreme hazard facilities |

AS/NZS 1170.0:2002 outlines design criteria for the different BIC's based on a risk estimation procedure. Risk is defined as the combination of the likelihood (probability) of an event and the consequences (damages and/or loss of lives) of a particular hazard. Since the landslide susceptibility map explicitly does not take time frame into account it does not display probabilities, so cannot be used for a detailed risk assessment. However, it can be used a guideline for potential new developments, or to highlight potential problem areas.

Table 7 (below) defines the susceptibility zones in terms of landslide potential. It also gives suggested actions. However, any regulations and rules to apply to each of the zones must be decided on by the Regional or District Councils, as this requires local knowledge of risk acceptance (tolerance) levels and will be a function of agreed local government policy.

**Table 7. Meanings and suggested actions relating to the five landslide susceptibility zones.**

| Susceptibility zone | Meaning | Suggested action |
|---|---|---|
| Very low | Effectively free of landslide hazard | Building and other activities need not take landslide hazard into account |
| Low | Landslides occur infrequently and will be small and easily managed | Building and other activities need only consider landslides as a minor threat |
| Moderate | Landslides occur infrequently, but on rare occasions may be large enough to cause property damage | Landslide hazard should be considered when planning a development, but need not be a restrictive concern, except where the proposed activity has high consequence for loss of life. For example, BIC 3, 4 or 5 |
| High | Damaging landslides occur occasionally and smaller landslides may be frequent | Building should be restricted to BIC 1 and 2a. A safe building site should be identified and mitigative measures designed by a suitably qualified person. Existing property owners in this zone should be notified of and educated about the hazard |
| Very high | Damaging landslides are common | Building should be restricted to BIC 1. Existing property owners in this zone should be notified of the landslide hazard and encouraged to take mitigative or avoidance actions |

This landslide hazard information should be included in regional and district plans. Rules can be applied to each of the susceptibility zones to control various aspects of development in landslide-prone areas, including design, construction, location, usage and density. These rules need to relate to the avoidance or reduction of exposure to landslide hazard (Saunders and Glassey, 2007). It can also be used to guide the regional development plan to avoid the development of landslide prone land and encourage the use of land shown as very low or low susceptibility to landslides.

When viewing the landslide susceptibility map, it is also useful to view the landslide inventory layers. These display the outlines of the disturbed areas of all the rainfall triggered landslides that were used to construct the model, and the mapped outlines of the large landslides triggered by earthquake and other means.

The landslide catalogue, when displayed in a GIS, can be queried to display all the landslides that have occurred in a specific area. This is useful in the early stages of an investigation to characterise the types, frequency and damages caused by landslides in that area. Further analysis of these landslide data is then possible to give probabilities of occurrence, rainfall amount trigger levels, etc. for some areas.

The landslide susceptibility map and the landslide catalogue should be used as a “first pass” assessment of landslide potential for an area of interest. This may be enough to persuade a potential developer to look for an alternative site, or to consider modification of development plans. They can also be used as supporting evidence for expert based geotechnical investigations.

Other potential uses of the landslide catalogue and susceptibility map include:

- Selection of suitable positions of power poles for new electricity transmission lines
- Planning the routes and design considerations for other lifelines
- Civil defence planning for heavy rainfall events
- Backcountry activity risk assessments
- Preliminary guidance for new road alignment
- Guidance on other land use changes

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## Glossary

***Hazard***: The probability or likelihood of a potentially damaging event occurring in a unit of time. Often expressed as the probability of occurrence of a given magnitude of event.

***Landslide catalogue:*** An historical list of landslides with dates and information relating to type of movement, size, damage caused, trigger, remedial measures in place, and any other pertinent information. Usually compiled from newspaper records, maintenance records, etc.

***Landslide inventory***: A spatial dataset of mapped landsides (often compiled from one trigger event), usually derived from aerial photograph interpretation (API), satellite image interpretation, and direct field mapping. Can also contain the same information types as a landslide catalogue.

***Landslide susceptibility:*** A quantitative or qualitative assessment of the classification, volume (or area), and spatial distribution of landslides which exist or potentially may occur in a given area. Although it is anticipated that landsliding will be more frequent in the more susceptible areas, timeframe is explicitly not taken into account in a susceptibility analysis.

***Raster:*** A spatial data model that defines space as an array of equally sized cells arranged in rows and columns, and composed of single or multiple bands. Each cell contains an attribute value and location coordinates. Unlike a vector structure, which stores coordinates explicitly, raster coordinates are contained in the ordering of the matrix. Groups of cells that share the same value represent the same type of geographic feature.

***Risk***: A measure of the probability and severity of an adverse effect to health, property or the environment. Risk is often estimated by calculating the probability of an event of a given magnitude multiplied by the consequences.

***Vector:*** A coordinate-based data model that represents geographic features as points, lines, and polygons. Each point feature is represented as a single coordinate pair, while line and polygon features are represented as ordered lists of vertices. Attributes are associated with each vector feature, as opposed to a raster data model, which associates attributes with grid cells.

***Vulnerability:*** The degree of loss to a given entity within the area affected by a landslide. For property it will be expressed as the damage relative to the value of the property; for people it is expressed as the probability of loss of life.

***Zoning:*** The division of land into homogeneous areas and their ranking according to degrees of actual or potential landslide susceptibility.